

**Dynamics, interactions and ecosystem implications of
mesoscale eddies formed in the southern region of
Madagascar**

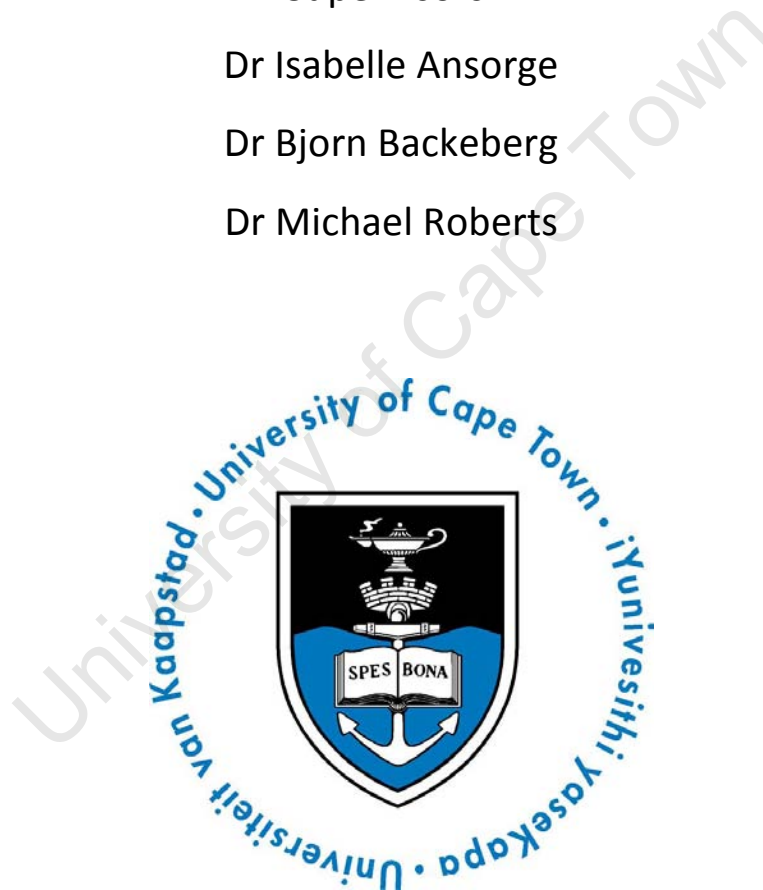
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Climate Dynamics.

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Abstract

Several species of marine organisms occurring off the southern African coast have been found to be identical to those occurring in the Madagascan coastal water although the reason for this is unknown. It has been proposed that eddies act as a vector of transport for planktonic larvae from the Madagascar island to the southern African east coast. In this study it is shown that eddies spawned off southern Madagascar entrain chlorophyll-a rich coastal waters into their periphery. This is indicative of the mechanism whereby organisms could become entrained in eddies. Approximately one eddy per year, usually cyclonic, interacts with the southern Madagascan coast, then from its origin crosses the southern Mozambique Channel and arrives at the African coast where it dissipates. By tracking eddies and combining their trajectories with drifter data and satellite remote sensing observations of ocean colour, it is shown that chlorophyll-a rich waters are entrained within the eddies, and these waters are mostly conserved during their passage across the channel. This study suggests that biota may be transported from Madagascar to Africa in eddies, providing further evidence that eddies are potentially a viable mechanism for the transport of organisms across the southern Mozambique Channel.

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1. Introduction

Source region eddies of the Agulhas Current are an important contributor to the flow (Schouten et al., 2002; Siedler et al., 2009) and variability of the Agulhas Current (Backeberg et al., 2008). Mesoscale eddies formed south of Madagascar also play a central role in the upwelling of deep, nutrient rich water into the ocean's euphotic zone thus encouraging the growth of phytoplankton (Quartly and Srokosz, 2004). Cyclonic eddies in this region rotate in a clockwise direction and their associated surface divergence results in upwelling in the eddies' cores (Quartly and Srokosz, 2004). They are comprised predominantly of chlorophyll-a rich shelf waters from southern Madagascar (Quartly and Srokosz, 2004) and are therefore clearly visible using ocean colour. As these eddies propagate offshore they carry Madagascan coastal water away from the coast (Quartly and Srokosz, 2004; Tew-Kai and Marsac, 2009)(Figure 1). Ocean rings and eddies are known to carry salt, heat and biological material for periods of weeks to months (Mooers and Robinson, 1984; Lobel and Robinson, 1986; Olson, 1991; Swart, 2010; Chelton et al., 2011). However, it is unclear whether eddies originating off Madagascar maintain their water mass characteristics or are able to carry organisms found in Madagascan coastal waters all the way across the southern Mozambique Channel and deposit them at the African coast.

The marine fauna of KwaZulu-Natal, on the east coast of South Africa, are comprised largely of species not indigenous to this region (Fenessay, 2012). Some species are also found in countries further north and in Madagascar, a subcontinent isolated by the Mozambique Channel (Fenessay, 2012). The question remains: how do these organisms arrive? It is hypothesized that the ocean circulation in this region may explain the distribution. Of particular interest are mesoscale eddies, which form south of Madagascar and have been observed to carry coastal water offshore. These eddies have been tracked and are commonly found in the northern Agulhas system (Halo et al., in press) and could act as a vehicle for biota originating from the coastal region off Madagascar. The internal circulation of an eddy, resulting in the upwelling of nutrients in the core and biological production (Bakun, 2006; Roberts et al., in

press), is thought to allow fauna to survive for this period. For example, the spiny lobster *Panulirus homarus rubellus*, is only found on the southeastern African coast and Madagascan coast (Holthuis; 1991). It's larvae are dispersed by ocean currents in the region and long-lived planktonic larval phase of up to six months, makes it a suitable candidate for passive transport across the southern Mozambique Channel in an eddy (Berry 1974a, Berry 1974b). Upon arrival it is thought that the interaction of an eddy with the African continental shelf causes the eddy to leave a filament of water trailing behind it (Shi and Nof, 1993; Nof 1999); thus providing a mechanism for organisms to be deposited on the southern African coast. This study has been termed "The Suitcase Project" as it describes the possible transport of a species from Madagascar to the southern African coast in eddies. This mechanism is important when estimating species population numbers, as well as the future fitness of populations which could be assisted by a regular larval supply from southern Madagascar (Fenesty, 2012).

Numerous different theories for the mechanism of formation of Madagascar eddies have been proposed but the circulation in the region is complex and therefore not easily understood (Lutjeharms, 1988a; Quartly and Srokosz, 2002; de Ruijter et al., 2004, Siedler et al., 2009; Ridderinkhof et al., 2013; Halo et al., in press). Our knowledge on the dynamics and interactions of these mesoscale eddies formed south of Madagascar remains rudimentary. It is unclear whether a regular eddy pathway for larval transport exists between Madagascar and the southern African coast.

The aim of this study is to explore the dynamics, interactions and resulting ecosystem implications of eddies formed south of Madagascar. The origin and frequency of eddy interactions with the southern Madagascan coast and later with the southern African coast is investigated to test the plausibility of the "Suitcase" hypothesis. Properties of the Madagascar eddies, including radii, amplitudes, circum-averaged speeds and directions of rotation, are compared to those of eddies propagating southwards down the Mozambique Channel. In-situ and satellite data are used, including eddy properties derived from an automated eddy tracking algorithm using satellite altimetry data, to analyse the following:

1. The interaction of eddies with the Madagascan coastline.
2. The evolution of the properties of the eddies on their westward pathway towards the African coastline.
3. Whether or not water within the eddies is conserved during the crossing of the southern Mozambique Channel.

By doing this, this study will provide a greater understanding of the mesoscale circulation in the region south of Madagascar and determine whether or not Madagascan eddies are a feasible mechanism in the relocation of biota across the southern Mozambique Channel.

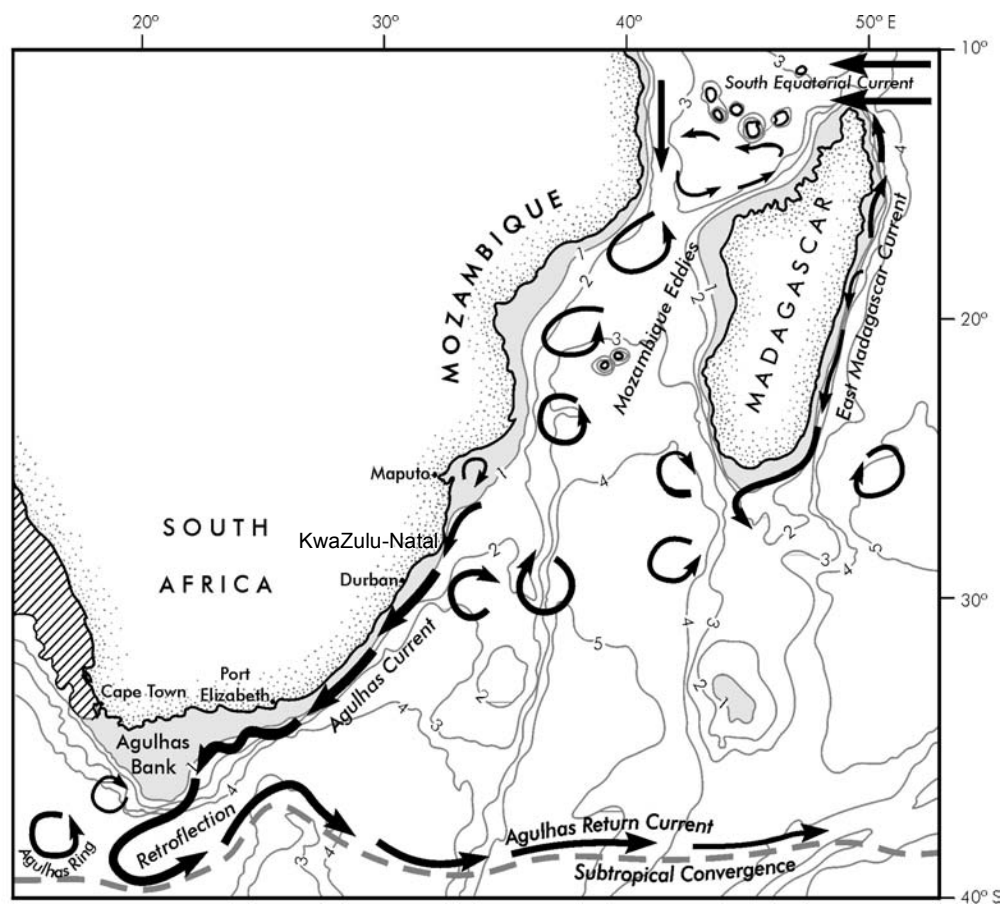


Figure 1: The prominent circulation features of the greater Agulhas Current system. The anti-cyclonic circulation of the Comoros Basin is shown, as is the mesoscale eddy activity in the Mozambique Channel and south of Madagascar. Both anti-cyclonic and cyclonic eddies propagate towards the Agulhas Current. Other important currents are also shown on this map including the East Madagascar Current (EMC). The southern branch of the East Madagascar Current, known as the South East Madagascar Current (SEMC) retroflects and eddies form here and propagate across the channel. (Source: Lutjeharms, 2006).

2. The Agulhas Current System

The Agulhas Current is the western boundary current of the South Indian Ocean, flowing polewards along South Africa's East Coast. The source waters of the current are derived from a combination of recirculation from the South-West Indian Ocean sub-gyre, flow through the Mozambique Channel and from the South East Madagascar Current (SEMC) (Stramma and Lutjeharms, 1997). The flow in the channel and from the SEMC consists primarily of mesoscale eddies, which propagate towards the Agulhas Current (Schouten et al., 2002). Both cyclonic and anti-cyclonic eddies form south and east of Madagascar, often as dipoles or multi-poles and are known to interact regularly with and entrain the Madagascan coastal waters (Halo et al., in press; Ridderinkhof et al., 2013). If the eddies are able to transport unique water properties and organisms across the southern Mozambique Channel, these source region eddies are potentially an important mechanism of connectivity between Madagascan and the Southern African coast.

2.1 The Northern Agulhas Current

The Agulhas Current is the strongest western boundary current in the Southern Hemisphere and forms part of the South-West Indian Ocean sub-gyre. It commences at approximately 27°S (Biastoch and Krauss, 1999; Backeberg et al., 2008) and flows southwestwards along the east coast of southern Africa (Rennell, 1832). In the northern extent, the current follows the narrow continental shelf edge closely with surface flow faster than 2m.s^{-1} (Lutjeharms, 2006). Variability in the northern Agulhas Current is influenced by mesoscale eddies originating from the source region of the current (Schouten et al., 2002; Backeberg et al., 2008), which propagate into the offshore edge of the Agulhas Current. These have been shown to destabilise the current and trigger cyclonic meanders known as Natal Pulses (Schouten et al., 2002; Backeberg et al., 2008), which then propagate polewards along the coast (van Leeuwen et al., 2000; Backeberg et al., 2008).

Agulhas source region eddies, originating from the Mozambique Channel as well as east and south of Madagascar at the southern extension of the East Madagascar Current, are known to be important contributors to the total volume transport in the Agulhas Current (de Ruijter et al., 2002; Schouten et al., 2002; Siedler et al., 2009). A transport of 15Sv from the southward flow in Mozambique Channel (de Ruijter et al., 2002); 25Sv from the South East Madagascar Current, as well as 30Sv from the South-West Indian ocean sub-gyre recirculation, all contribute to the flow of the Agulhas Current (Stramma and Lutjeharms, 1997). Flow from the Mozambique Channel and from east and south of Madagascar consists of mesoscale anti-cyclonic and cyclonic eddies (Schouten et al., 2002). Past research (Schouten et al., 2002) has shown the variability and complexity of the circulation in the source region of the current (Hancke et al., 2012). Both Mozambique Channel and Madagascar eddies propagate into the source region of the Agulhas Current and can travel as far down the current as the Agulhas retroflexion region (Schouten et al., 2002, Backeberg et al., 2008). Rings and eddies are known to transport unique water masses over long distances (Olson, 1991) and consequently, source region eddies contribute periodically to the total volume transport in the Agulhas Current (Lutjeharms, 2006).

2.2 The Mozambique Current

Early hydrographic surveys in the source region of the Agulhas Current suggested that the Agulhas Current was an extension of the Mozambique Current (Harris, 1972) (Figure 2). However, first studies by Saetre and da Silva (1984) based on a study using all available hydrographic data, suggested that the Mozambique Channel flow consisted of large anti-cyclonic eddies and smaller cyclonic eddies. This has since been confirmed using a wide range of remotely sensed data which is now available for the region (Gordon et al., 1983; Quartly and Srokosz, 2004). Satellite altimetry observations have shown that there is a large amount of variability in the Mozambique Channel, suggesting that the dominant flow is in the form of mesoscale eddies (Schouten et al., 2002).

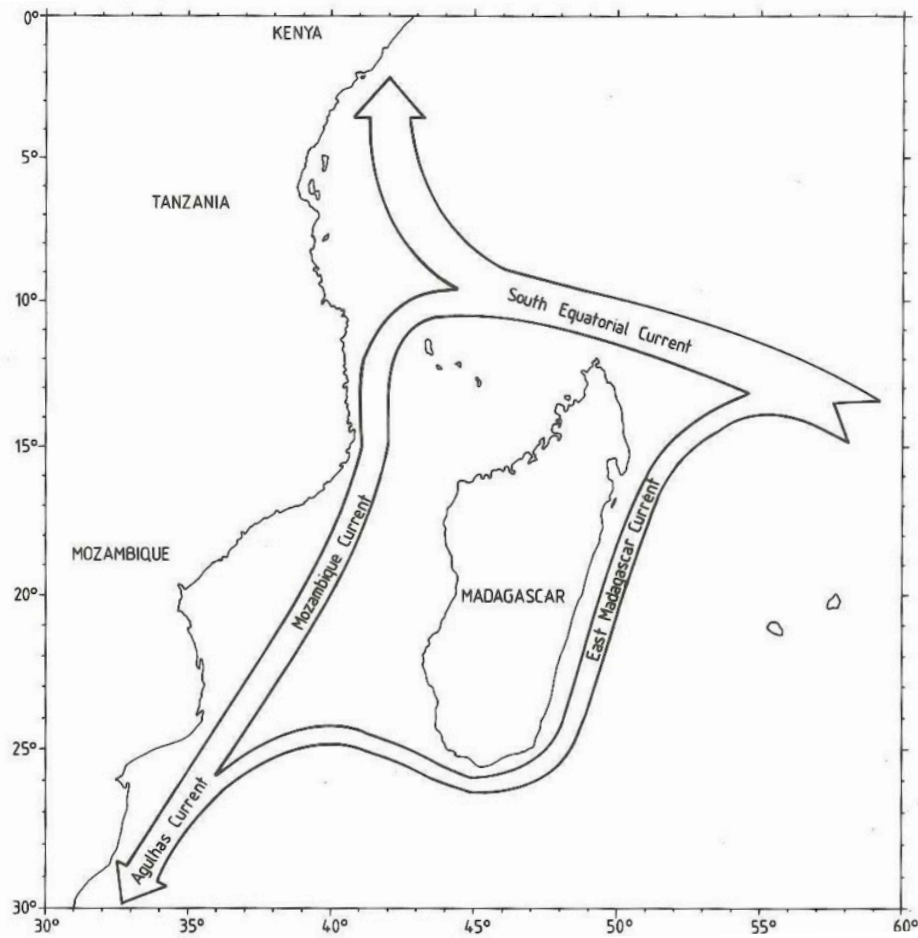


Figure 2: A historical view of the currents in the south west Indian Ocean. Currents shown are the South Equatorial Current, East Madagascar Current, Mozambique Current, and Agulhas Current (Source: Saetre, 1985).

2.3 Mozambique Channel Eddies

Satellite altimetry observations and modelling studies (Halo et al., 2013) confirm that the Mozambique Channel is dominated by a series of anti-cyclonic and cyclonic eddies (Figure 3). Anti-cyclonic eddies are known to form in the northern part of the Mozambique Channel near 12°S, as well as in the central or eastern sectors of the channel (Halo et al., 2013). It was suggested by Ridderinkhof and de Ruijter (2003) that the anti-cyclonic eddies form when an unstable, strong, eastward flowing current moves over the Davie Ridge. Cyclonic eddies have not been studied in as much detail as their counterparts, however, their formation is possibly influenced by

the local bathymetry (Saetre and da Silva, 1984). Research shows that most Mozambique Channel cyclonic eddies form along the eastern side of the channel (Halo et al., 2013). Drifter tracks indicate that flow on the western side of the channel is predominantly anti-cyclonic whilst the eastern side of the channel has more cyclonic eddy activity (Hancke et al., 2012).

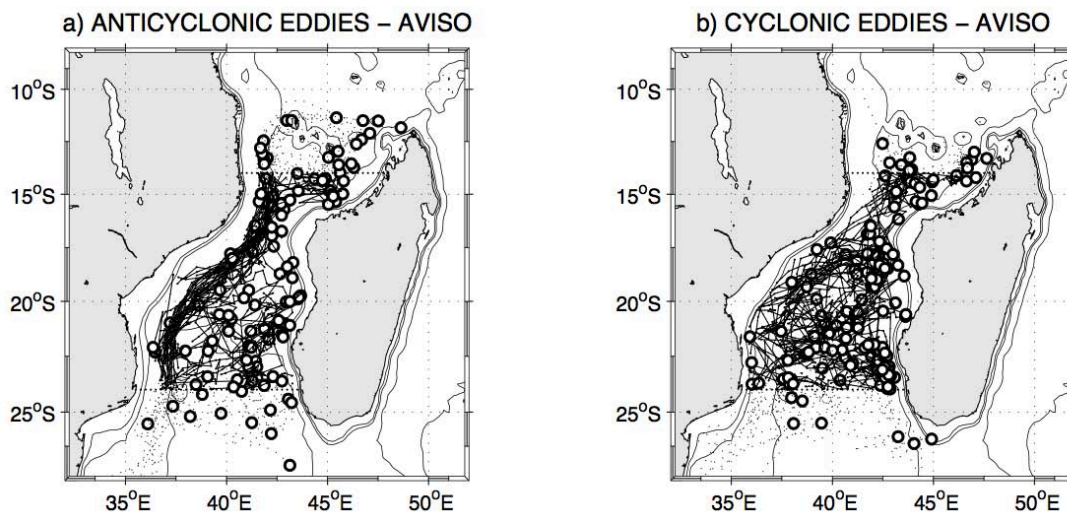


Figure 3: Formation sites and trajectories of a) anti-cyclonic and b) cyclonic eddies in the Mozambique Channel using a subset of AVISO altimetry data. Black circles indicate eddy formation sites and the lines indicate their trajectories. Isobath countours are shown at 500, 1000, 3000 and 5000m (Source: Halo et al., 2013).

Past investigations indicate that between 4 and 6 anti-cyclonic eddies occur in the narrows of the northern Mozambique Channel every year (Ridderinkhof and de Ruijter, 2003; Backeberg et al., 2008; Halo et al., 2013) with an average of 17.1 anticyclonic eddies occurring annually in the channel between 14 and 24°S (Halo et al., 2013) (Table 1). Recent studies have shown that cyclonic eddies dominate this region with an average of 22 eddies per year (Halo et al., 2013). Cyclonic eddies forming in the channel are typically smaller in size than their anti-cyclonic counterparts (Halo et al., 2013) which have a diameter of approximately 300 to 400 km (Schouten et al., 2002). The study by Halo et al. (2013) suggests the mean radius of anti-cyclonic eddies in the channel to be 157km compared to a radius of 139km associated with the cyclonic features. Drifter patterns show that once surface water becomes entrained into anti-cyclonic eddies, they can be transported from their

point of origin in the Comoros Basin, southwards through the Mozambique Channel (Hancke et al., 2012). Research by Backeberg et al. (2008) shows that anti-cyclonic eddies from the Mozambique Channel, propagate southwards at a speed of $7 \pm 2 \text{ km.day}^{-1}$, and move into the northern Agulhas Current with approximately $\frac{2}{3}$ of the eddies propagating as far the Agulhas retroflexion region. Anti-cyclonic eddies have an average lifetime of 101 days, which is greater than that of the cyclonic eddy which on average has a duration of 85 days (Halo et al., 2013).

Eddy	N [eddies. year ⁻¹]	$\bar{\tau}$ [day]	$\bar{\eta}$ [cm]	\bar{L} [km]
Altimetry				
Cyclones	22.1	85.0	11.0	139.0
Anti-cyclones	17.1	101.0	14.0	157.0

Table 1: The properties of cyclonic and anti-cyclonic eddies in the Mozambique Channel calculated using AVISO altimetry data from October 1992 to March 2010. Properties include number of eddies per year (N[eddies.year⁻¹]), mean life time of the eddies ($\bar{\tau}$ [day]), mean amplitude ($\bar{\eta}$ [cm]), and mean diameter (\bar{L} [km]) (Source: Halo et al., 2013).

2.4 The South East Madagascar Current

The westward flowing South East Equatorial Current splits into the North East Madagascar Current (NEMC) and the South East Madagascar Current (SEMC) at approximately 17°S (Lutjeharms and Machu, 2000) as it reaches the East coast of Madagascar (Lutjeharms, 2006). The poleward flowing SEMC, like the Agulhas Current, is thought to be strongest during the northeast monsoon season (Saetre, 1985) with an average velocity of 1 m.s^{-1} (Ridderinkhof et al., 2013).

The SEMC was originally thought to be a direct tributary of the Agulhas Current. Supplementary research however, suggests that there is no direct connection between the SEMC and the Agulhas Current, instead showing a retroflexion of the SEMC south of Madagascar (Lutjeharms, 1988; Quartly and Srokosz, 2002). The retroflexion of the SEMC is described by many as similar to that of the Agulhas Current, as inertia is thought

to separate both currents from their respective landmasses (de Ruijter et al., 2004). Similar to the Agulhas Current, it is thought that topography plays a role and that the SEMC retroflects because of the presence of the shallow Madagascar Ridge south of the island (Halo, 2008). In some places the ridge is as shallow as 1000m (Quartly and Srokosz, 2004) and a study undertaken by Halo (2008) shows that the Madagascar Ridge increases the variability of the flow in the Mozambique Channel and south of Madagascar and controls the SEMC retroflexion. One difference however, is that the background flow surrounding the SEMC is westward and not eastward as in the case of the Agulhas Current (de Ruijter et al., 2004). The SEMC is thought to interact with the topography and its retroflexion triggers anti-cyclonic eddy formation (de Ruijter et al., 2004, Halo, 2008; Halo et al., in press). Studies suggest that cyclonic eddies are lee eddies, drawing water from the inshore edge of the SEMC, that form as a result of friction between the SEMC and the continental shelf (de Ruijter et al., 2004, Ridderinkhof et al., 2013).

Additional studies suggest that the SEMC alternates between periods of retroflexion and no retroflexion (de Ruijter et al., 2004; Siedler et al., 2009; Halo et al., in press). Research conducted by Siedler et al. (2009) also shows another phase of the current- which is that on occasion the SEMC has two branches; one which retroflects forming the South Indian Ocean Counter Current (SICC), and another which continues in the direction of the Agulhas Current (Figure 4). They found that flow from the SEMC retroflexion constitutes 40% of the SICC. This theory however, is not supported by in-situ data analysis as the SICC is much shallower than the SEMC, meaning only the near-surface part of the SEMC would retroflect (Palastanga et al., 2007). Halo et al. (in press) imply that a connection between the SEMC and SICC is probably obtained through the shedding of anti-cyclonic eddies. It has been suggested that when the SEMC is a westward jet, it breaks down to generate a contra-rotating pair of eddies known as a dipole (de Ruijter et al., 2004; Ridderinkhof et al., 2013). Ridderinkhof et al. (2013) propose that this is the permanent phase of the current and that where the SEMC separates from the southern tip of Madagascar, there is a similar amount of cyclonic and anti-cyclonic shear across the jet, and the jet breaks down causing symmetric dipoles to form. Both cyclonic and anti-cyclonic eddies are formed southwest of

Madagascar where the SEMC moves away from the Madagascar shelf (de Ruijter et al., 2004; Ridderinkhof et al., 2013).

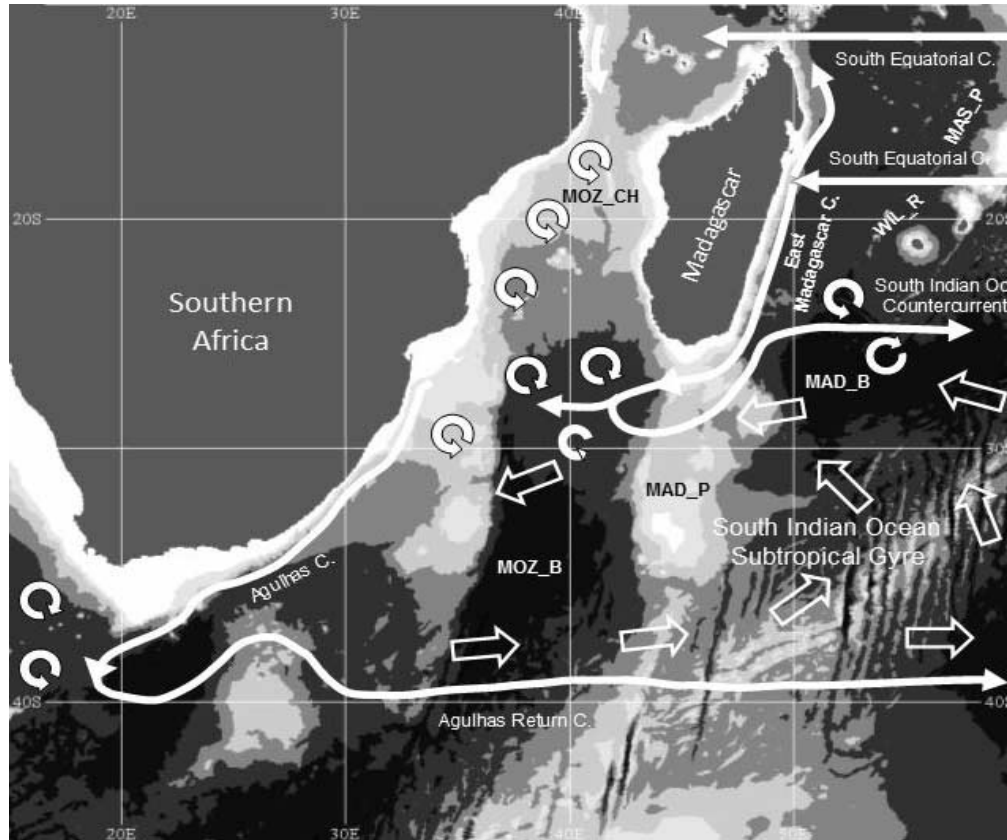


Figure 4: Schematic of the South East Madagascar Current (SEMC) and Agulhas Current retroflexions. In this case the SEMC retroflexion is called the South Indian Ocean Countercurrent. Geographic features including the Madagascar Plateau (MAD_P), Mozambique Chanel (MOZ_CH), Mozambique Basin (MOZ_B), Madagascar Basin (MAD_B), Mascarene Plateau (MAS_P) and Wilshaw Ridge (WIL_R) are shown. Thin arrows show currents and the subtropical gyre is indicated by thick arrows (Source: Siedler et al., 2009).

2.5 Madagascar Eddies

A recent study conducted by Halo et al. (in press) investigating two different regions of enhanced eddy activity, one southeast (45.10°E to 51.10°E and 32°S to 24°S) and one southwest of Madagascar (39°E to 45°E and 32°S to 24°S), shows that the eddy formation mechanisms for these two regions are different. In the southeast region,

eddies are formed by barotropic instabilities, whereas in the southwest region, eddies are formed by both barotropic and baroclinic instabilities (Halo et al., in press). Their study shows that eddies in the southwest region are larger and stronger than those in the southeast region. In the southeast region, anti-cyclonic eddies had a radius of $141 \pm 32\text{km}$ whereas cyclonic eddies had a radius of $129 \pm 34\text{km}$ (Halo et al., in press). The southwest anti-cyclonic eddies were bigger with a radius of $145 \pm 37\text{km}$ and southwest cyclonic eddies had a radius of $140 \pm 37\text{km}$ (Halo et al., in press).

Research by de Ruijter et al. (2004) shows that southeast of Madagascar dipoles regularly occur and propagate westwards across the southern Mozambique Channel, and a recent study suggests a frequency of approximately 4-6 dipoles annually (Ridderinkhof et al., 2013). Periods of increased dipole formation do occur during the negative phases of both El Nino and Indian Ocean dipole events (de Ruijter et al., 2004). Madagascar dipoles have been shown to be approximately equal in strength (Ridderinkhof et al., 2013) and in radius (approximately 50-200km) (de Ruijter et al., 2004; Ridderinkhof et al., 2013; Halo et al., in press). Eddy dipoles have been shown to split and interact with other eddies in the region (de Ruijter et al., 2004, Ridderinkhof et al., 2013), as they move westwards across the channel towards the southern African coast (Quartly and Srokosz, 2004).

Drifters have been used to highlight the movement in the frontal field which exists between two eddies, known as interstitial flow (Hancke et al., 2012). A drifter caught in interstitial flow could move in the opposite direction to that of the eddies surrounding it and at a much greater speed (Hancke et al., 2012). Drifters which were in the SEMC made their way to the Mozambique shelf in these frontal zones between eddies (Hancke et al., 2012). Although it has never been shown, it is thought as an alternative to eddy transport, that organisms could possibly be carried across the southern Mozambique Channel in the frontal flow which exists between different eddies (Hancke et al., 2012).

The mesoscale circulation in the source region of the Agulhas Current is complex and for this reason the mechanism for eddy formation, particularly in the region south of Madagascar, is not clear. Eddies which form in the Mozambique Channel and south or east of Madagascar can be cyclonic or anti-cyclonic and propagate in the direction of the Agulhas Current. Some eddies join the current and can travel as far south as the Agulhas retroflection region, where warm, saline Agulhas rings are shed into the Atlantic Ocean. Madagascar eddies are known to entrain coastal waters from the southern region of the island (Quartly and Srokosz, 2004). However, there has been little investigation into the frequency of this interaction, as well as the retention and later leakage or dumping of these waters from the eddies as they approach the Agulhas Current and African coastline. It is therefore unknown whether biota could be transported across the southern Mozambique Channel inside eddies to the southern African coast.

3. Data and Methods

In this study the role of mesoscale turbulence south of Madagascar is investigated using a combination of in-situ and satellite data. In-situ measurements were collected using drifters, an Underwater Temperature Recorder and a Thermosalinograph. Satellite data used includes AVISO Mean Sea Level Anomaly data and Mean Absolute Dynamic Topography data as well as MODIS chlorophyll-a data and OSTIA sea surface temperature data. Eddy trajectories and properties are monitored using an eddy tracking algorithm in order to investigate potential pathways between Madagascar and the southern African coast.

3.1 Satellite altimetry derived eddy properties

An automated global eddy tracking algorithm developed by Chelton and Schlax is able to track mesoscale eddies by following satellite altimeter observations of closed sea surface height (SSH) contours (Chelton et al., 2011). The algorithm is applied to maps of SSH from satellite altimeter observations. Once large-scale variability from the warming and cooling of the sea surface has been filtered out by the algorithm, a series of maps with $\frac{1}{4} \times \frac{1}{4}^\circ$ pixels are obtained at 7 day time-steps (Chelton et al., 2011). The eddy tracking algorithm defines eddies as having an amplitude of at least 1cm, and in each SSH map an eddy consists of closed SSH contours containing a minimum of 8 and a maximum 1000 pixels (SSH data points) with the distance between connected pixels being less than a specified amount which is dependent on the eddies' latitude. SSH must fall between -100cm and +100cm. For anti-cyclonic eddies, which have a concave-down SSH, the SSH threshold must be greater than -100cm with a local SSH maximum (Chelton et al., 2011). A cyclonic eddy, would have a concave-up SSH and is therefore defined as having a SSH threshold less than 100cm, with a local SSH minimum (Chelton et al., 2011). Once an eddy is identified, the algorithm calculates different properties associated with the eddies at 7 day time-steps. These include eddy locations, directions of rotation, amplitudes, radii and circum-averaged speeds. The center of an eddy is tracked from one week to the next by searching for the eddy center closest to it's previous position (Chelton et al.,

2011). This procedure was used in this study to identify all eddies which interacted with the southern Madagascan coast between October 1992 and April 2012.

The eddy data were gridded to $1^{\circ} \times 1^{\circ}$ grid, and the frequency of occurrence, the amplitudes, radii and circum-averaged speeds were compared for both cyclonic and anti-cyclonic eddies occurring south of Madagascar for the full period of the data. This method was also used to compare eddies forming in the Mozambique Channel to those forming south of Madagascar. The formation and termination sites of all eddies were also gridded using the same method in order to identify the dominant formation sites of both cyclonic and anti-cyclonic eddies in the region south of Madagascar from October 1992 until April 2012.

There are a vast number of eddies in the region and therefore it was necessary to subset the data through a smaller region on the southern Madagascan coast, to filter out all observations which weren't applicable for this study (Figure 5). This region was defined to be $22^{\circ}\text{--}27^{\circ}\text{S}$ and $42.5^{\circ}\text{--}49^{\circ}\text{E}$. The data were further reduced by separating cyclonic eddies from anti-cyclonic eddies in order to observe the similarities and differences of properties and abundance of counter-rotating eddies. The development of these eddies as they crossed the Mozambique Channel was evaluated using the subsetting data set.

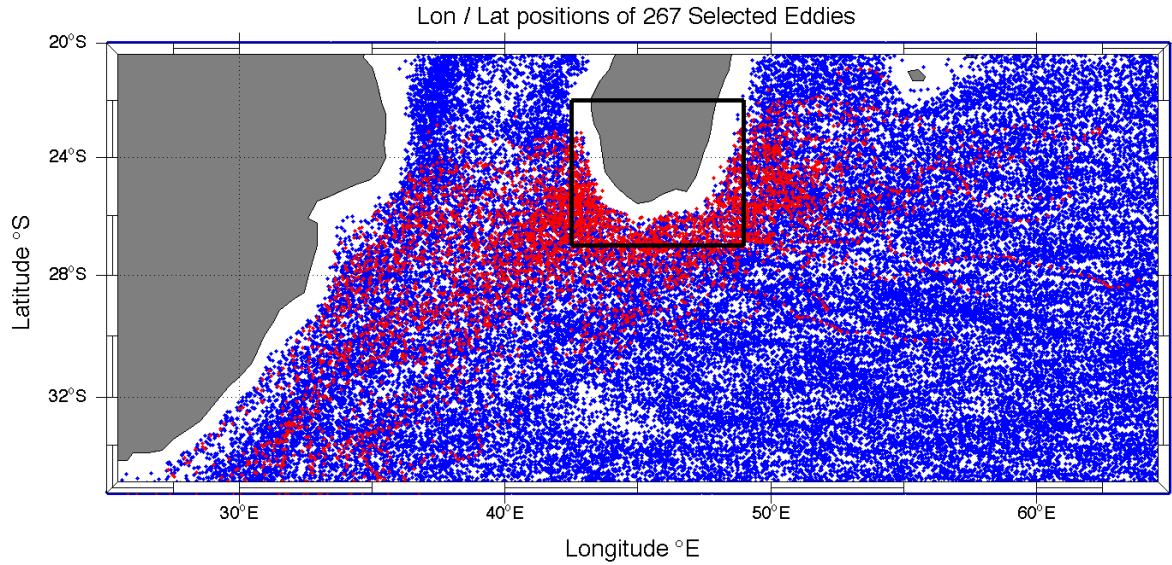


Figure 5: The positions of all eddies which have occurred in the domain between October 1992 and April 2012 are shown in dots. The red dots indicate only those eddies which pass through the black rectangle and therefore the eddies which were important for this study.

Using a calculation described by Chelton et al. (2011), the Chelton data were used to calculate whether or not water is conserved in Madagascar eddies as they cross the southern Mozambique Channel. The calculation states that if the maximum eddy-rotation speed is larger than its translation velocity then water is retained in the eddy. Conservation of water in eddies is essential if a pathway for transport of unique water masses as well as for biological material does exist between Madagascar and the southern African coast.

3.2 Satellite remote sensing data

3.2.1 Satellite altimetry data

The eddy tracking data set is derived from satellite altimeter observations, and there is no data close to the coast. When the water depth is shallow, the radar echo sometimes reflects off both land and water giving an inaccurate reading, which is not processed (Bouffard et al., 2010). The data are also interpolated in both space and time and it was therefore necessary to validate the eddy data by comparing it to weekly AVISO Mean Sea Level Anomaly (SLA) data. This was done, using a series of case studies, to verify whether or not all eddies of interest are captured and

correctly tracked by the automated eddy tracking algorithm. SLA data from October 1992 until February 2012 were used in this study.

Mean Absolute Dynamic Topography (MADT) data from AVISO from October 1992 until February 2012 were used to plot geostrophic velocities and observe the interactions of both cyclonic and anti-cyclonic eddies with the southern Madagascan Coast. However, as the eddy data set is created from AVISO altimetry data it cannot be verified with AVISO altimetry data alone. Several figures were overlaid with ETOPO2 topography contours to see the role that the topography plays in the eddies' trajectories. This 2 minute gridded topography data were taken from the National Oceanographic and Atmospheric Administration website (<http://www.ngdc.noaa.gov>).

3.2.2 MODIS chlorophyll-a data

Monthly composites of chlorophyll-a data from the MyOcean website (<ftp://myocean.artov.isac.cnr.it/core/>) were combined with eddy tracking data set to obtain a more accurate and a better understanding of the interactions of the coastal waters with the eddies. The 9km resolution, monthly chlorophyll-a data, which is measured by a spectroradiometer, were examined from 30.09.1997 until 31.01.2010. It was thought that monthly data were not sufficient to observe eddy interactions, which could happen over a shorter time scale, and therefore Moderate Resolution Imaging Spectroradiometer (MODIS) daily chlorophyll-a data were retrieved from <ftp://www.afro-sea.org.za/>. The daily chlorophyll-a data were obtained for the Mozambique Channel region for the period of 04.07.2002 until 17.09.2013 and were also used to try and identify the mechanism of formation of these eddies in the so-called retroflexion region of the South East Madagascar Current. A major limitation of the daily chlorophyll-a data is that cloud cover in the region of interest often results in little or no data collection.

3.2.3 Satellite observations of sea surface temperature

Sea Surface Temperature (SST) Data from Operational Sea Surface Temperature and Sea Ice Analysis (OSTIA), available at <http://ghrsst-pp.metoffice.com> for the period of 13.04.2006 until 14.03.2012 were used to try and better observe the retroflection of the South East Madagascar Current and the mechanism for the formation of eddies south of Madagascar. OSTIA uses a combination of satellite data from the Group for High Resolution Sea Surface Temperature project (GHRSSST) and in-situ data to calculate the SST. From this, a combination of SST and other data sets were used to gain a more complete understanding of eddy dynamics in the region.

3.3 UTR data

Eddy interactions with the coastlines are known to induce slope upwelling (Roberts et al., 2006; Morris et al., 2013). An underwater temperature recorder (UTR), situated at a location of 27°24'53"S and 32°43'36"E and a depth of 18m, in Sodwana Bay, South Africa, was therefore used to count the number of eddy-slope interactions in the region. Eddies tracked by the Chelton data set cannot be seen near the coast and therefore, the presence of an eddy visible by the sea level anomaly, along with a corresponding drop in temperature recorded by the hourly UTR data were used to confirm the interactions of Madagascan eddies with Sodwana Bay. UTR data from the Centre for in situ Observational Oceanography were used (<http://www.cfoo.co.za>).

3.4 SVP drifter data

On 12.04.2013, three surface drifters (ID numbers: 101939, 101950 and 101944) with 15m drogues were deployed at 26° 44.4556' S and 38° 20.089'E in a cyclonic eddy which formed south of Madagascar and was therefore possibly comprised of Madagascan coastal waters. Surface Velocity Program (SVP) drifters are lagrangian devices that drift with the surface currents in which they are placed, transmitting

their location every 6 hours. They are not only used to highlight the surface circulation in a region but are useful to observe the internal circulation of eddies. In this case, the drifters were used to investigate the potential of planktonic larvae to remain in the eddy as it crossed the Mozambique Channel and what happens if the drifters and eddy interacted with the southern African coast. It was thought that the drifter positions could be influenced by winds, and the 2 functioning drifter's positions were therefore overlaid on updated, daily MSLA data to see whether or not they remained in the eddy.

3.5 Thermosalinograph (TSG) data

TSG data collected on the R/V Meteor conducted in October 2013 were used to investigate the similarity of the surface waters of the SEMC to the surface waters of an anti-cyclonic eddy south of the island.

4. Results

In this study the mesoscale circulation in the region south of Madagascar has been investigated in order to determine whether a pathway between Madagascar and southern Africa exists for the transport of biota across the southern Mozambique Channel.

4.1 In-situ hydrographic data

An investigation into a ships trajectory clearly shows the ship passing through an anti-cyclonic eddy (Figure 6). Thermosalinograph data collected from the 15-16 October 2013 during the research cruise shows that the surface waters of an anti-cyclonic eddy have a 0.3 lower salinity than the surrounding waters. The results shows that the SEMC has a 0.3 lower salinity than the eddy. This is consistent with the idea that anti-cyclonic eddies form as a result of the reflection of the SEMC and would therefore contain lower salinity waters that one would expect to find in a current that has tropical origins. This results imply that the anti-cyclone is comprised partially but not fully of waters from the SEMC.

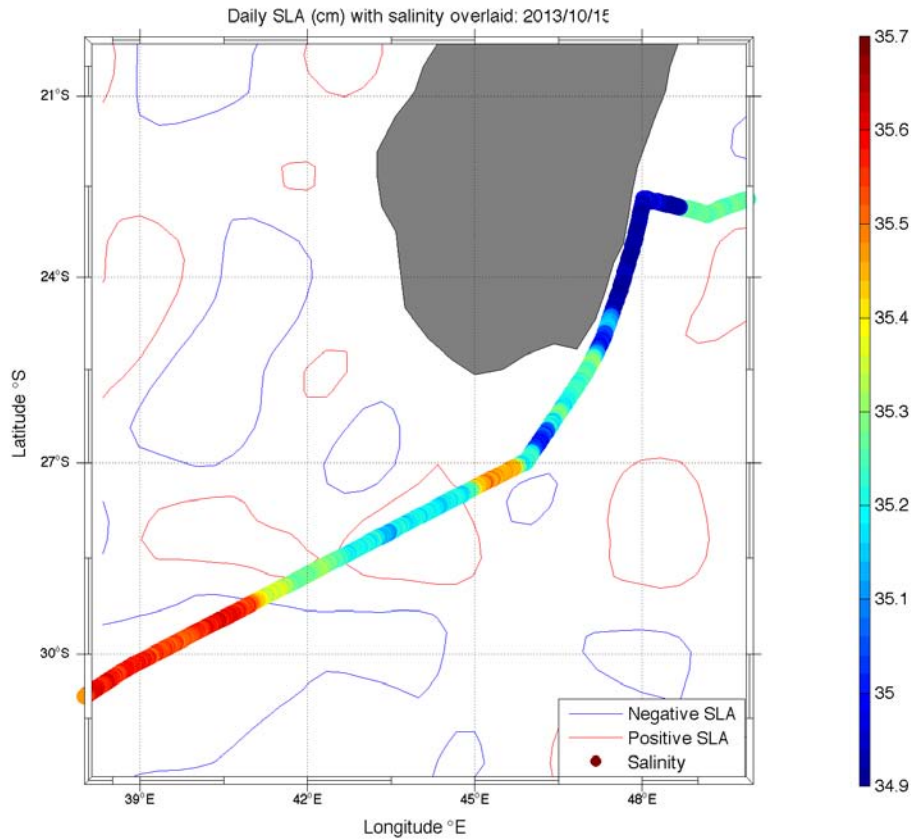


Figure 6: The cruise trajectory overlaid on MSLA contours of +10cm (red) and -10cm (blue). The cruise trajectory shows corresponding salinity data collected by a thermosalinograph for the cruise.

In order to study the trajectories of eddies across the southern Mozambique Channel, a case study was selected with the hope of seeing an eddy interaction with the Madagascan as well as the southern African coast.

4.2 Case study 1

A cyclonic eddy which occurred in 2013 was selected as a case study and tracked using near real time Mean Sea Level Anomaly (MSLA) data. Results show that the eddy successfully manages to cross the southern Mozambique Channel in a period of approximately 4 months to then interact with the southern African coast (Figure 7).

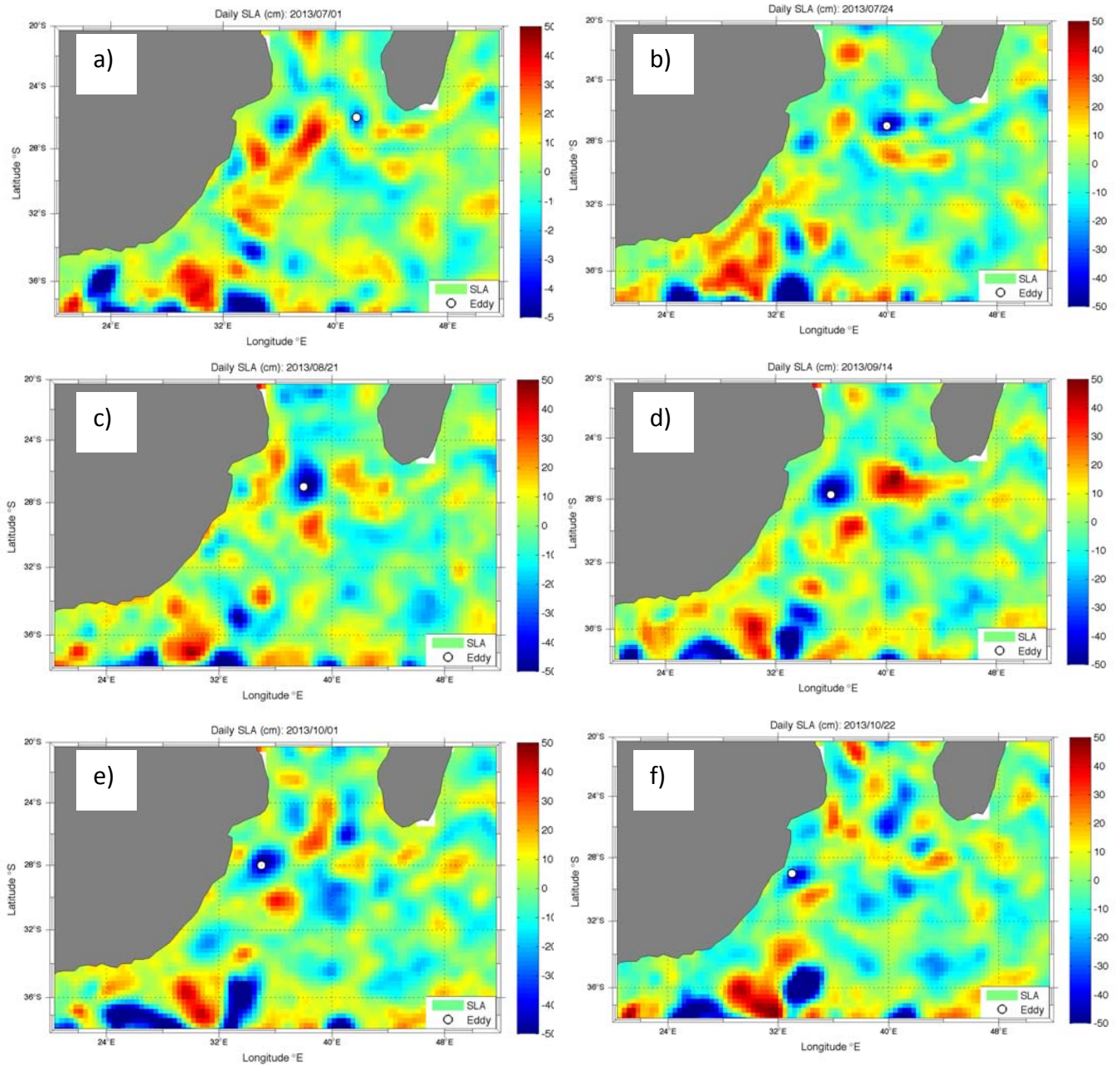


Figure 7: the daily AVISO MSLA as for (a) 01.07.2013, (b) 24.07.2013, (c) 21.08.2013, (d) 14.09.2013, (e) 01.10.2013 and (f) 22.10.2013 with the eddy position overlaid in a white circle.

4.3 Case study 2

A second case study using MSLA data as well as eddy tracking data was investigated to provide more detail of the propagation of cyclonic eddies across the southern Mozambique Channel. The eddy was first tracked by the eddy tracking algorithm on 30.07.2008 near the south coast of Madagascar. As with most Madagascar eddies

the amplitude of the eddy increases as it moves away from the coast, from 0cm when it formed, to a maximum of 60cm (Figure 8). The amplitude of the eddy then decreases approximately 10cm as the eddy interacts with another mesoscale feature. The eddy manages to survive this interaction, and the amplitude then increases again to 50cm before the eddy begins to interact with the Agulhas Current and eventually the African coastline where it dissipates completely. This interaction is not shown with the Chelton data set alone, but is evident upon examination of AVISO MSLA data.

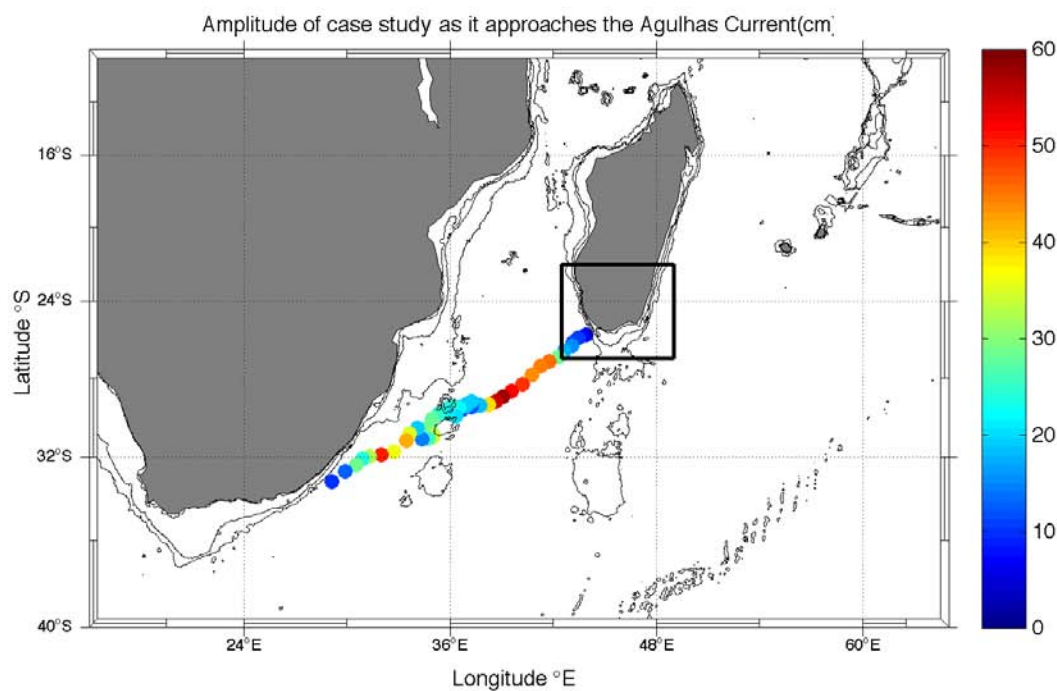


Figure 8: The trajectory and amplitude of a cyclonic eddy used in the case study. Bathymetry contours have been overlaid.

The AVISO MSLA was investigated for the case study eddy. The automated eddy tracking algorithm first tracks the eddy on 30.07.2008 (Figure 9b). The Sea level anomaly for the weeks prior was investigated to see if the eddy did in fact exist before this but was too close to the coast for it to be tracked by the eddy tracking algorithm. In the week prior to the eddy being tracked, little or no negative sea level anomaly was present, suggesting that the eddy-tracking algorithm is an accurate representation of eddy trajectories (Figure 9a).

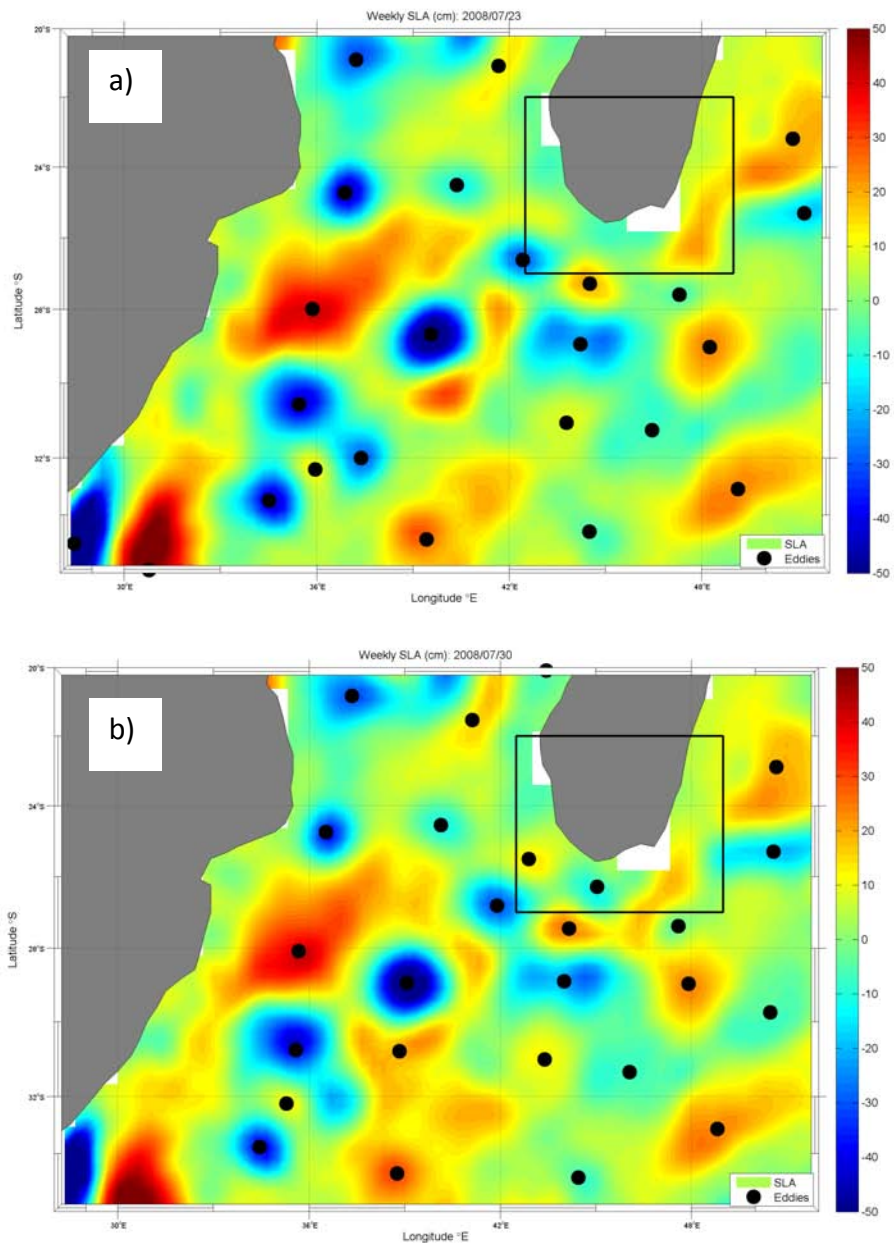


Figure 9: AVISO Mean Sea Level Anomaly (MSLA) with corresponding eddy positions for (a) 23.07.2008, the week before the eddy is tracked by the Chelton data set (b) 30.07.2008, the first week the eddy is detected by the algorithm. Note the presence of a cyclonic eddy within the black rectangle (blue in colour).

An investigation of the MSLA shows the cyclonic eddy impacting the southern African coast on 18.02.2009 (Figure 10a). The algorithm last tracks the eddy on 04.03.2009 (Figure 10b), after which it is no longer identified by Chelton as an eddy. A negative sea level anomaly is however evident and moves down the current for several weeks afterwards (Figure not shown). This case of a cyclonic eddy highlights

the accuracy of the eddy tracking algorithm and shows a body of water moving from the Madagascan coast and across the southern Mozambique Channel to then interact with southern Africa, and confirms that a pathway exists between Madagascar and Southern Africa.

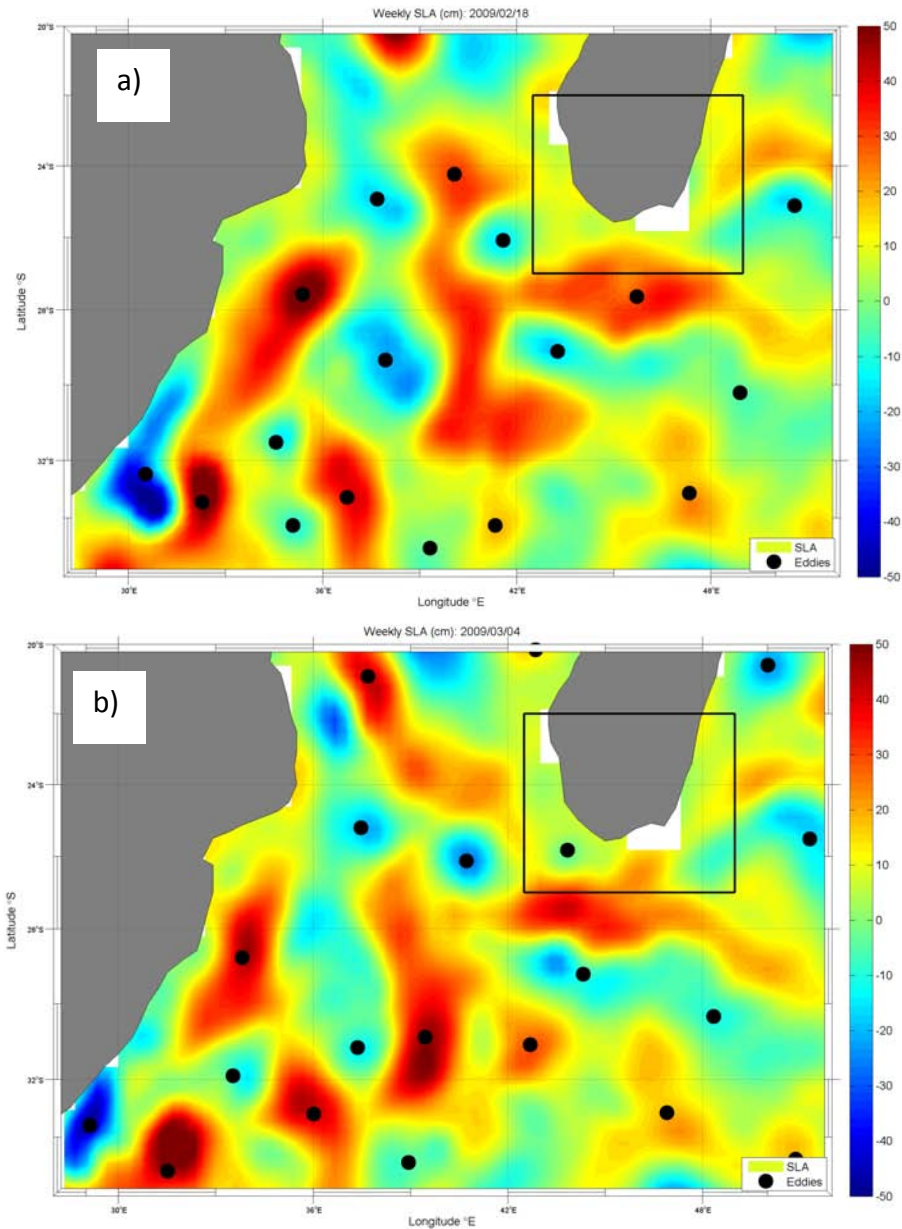


Figure 10: a) An image showing the weekly AVISO MSLA as well as corresponding Chelton eddy positions for 18.02.2009. b) An image showing the weekly AVISO MSLA as well as corresponding Chelton eddy positions for 04.03.2009. The black rectangle represents the region through which the Chelton eddies were subset. Note the presence of a cyclonic eddy against the southern African coast (blue in colour).

4.4 Eddy tracking data

Results from the eddy tracking algorithm indicate that both anti-cyclonic and cyclonic eddies are generated and terminated almost everywhere in the domain, although more eddies (up to 18 anti-cyclonic and 20 cyclonic in the same region between October 1992 and April 2012) are suggested to form on the west coast of Madagascar (Figure 11 and Figure 12) than in the open ocean where between 0 and 8 anti-cyclonic and cyclonic eddies have formed over 19.5 years. More eddies have dissipated close to the east coasts of Madagascar and the African continent than in the open ocean.

The main difference in regions of formation between anti-cyclonic and cyclonic eddies is in the southern region of Madagascar. Results from a $1^\circ \times 1^\circ$ grid show that the generation of anti-cyclonic eddies is mostly concentrated in the western ($43-44^\circ\text{E}$ and $25-26^\circ\text{S}$) and central southern coast of Madagascar ($45-46^\circ\text{E}$ and $27-28^\circ\text{S}$) (Figure 11a). In contrast, cyclonic eddies appear to generate in the south west coast of the island ($43-44^\circ\text{E}$ and $25-27^\circ\text{S}$) (Figure 11b). Results from Figure 11 also show that more cyclonic eddies have formed closer to the coast than anti-cyclonic eddies.

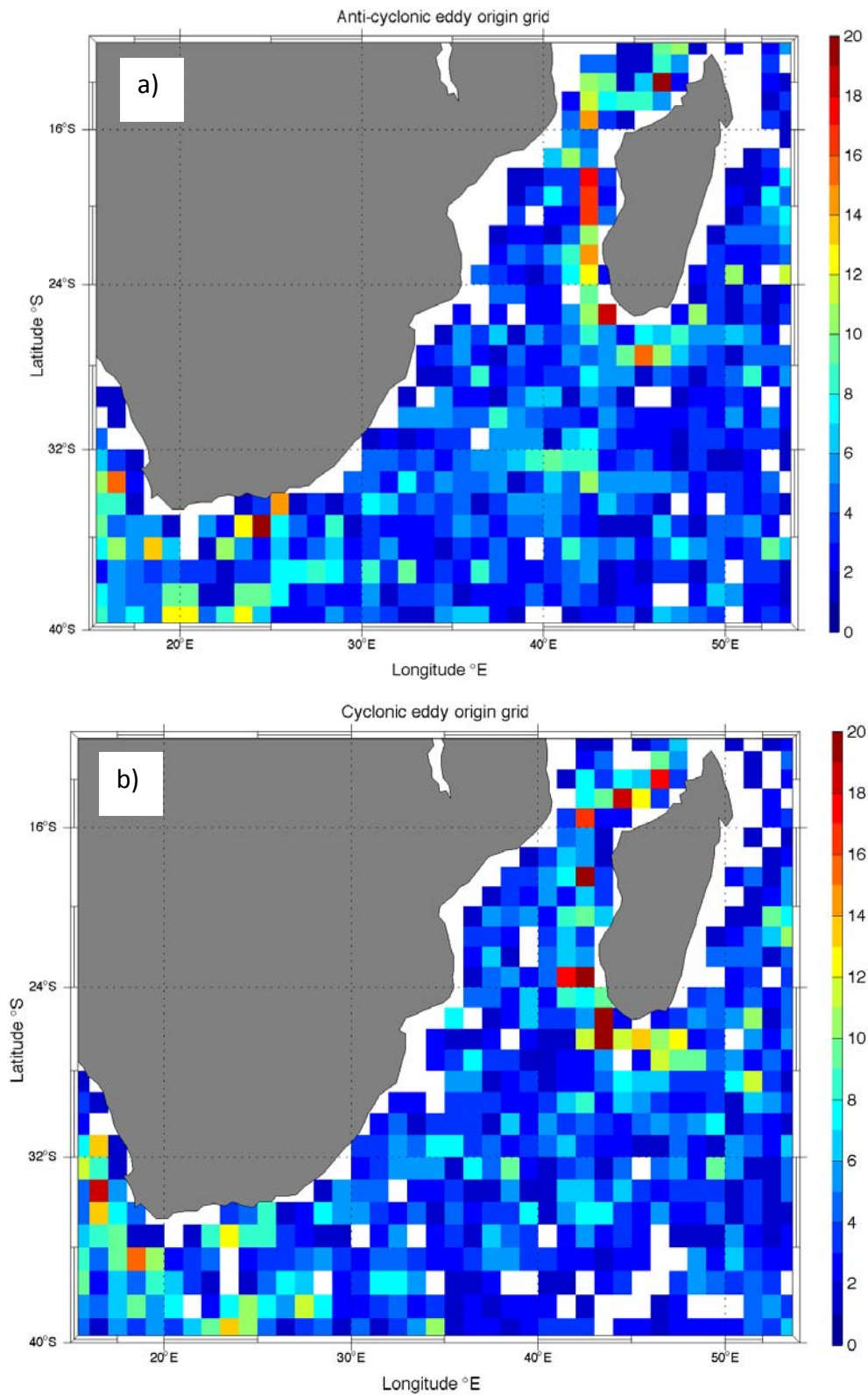


Figure 11: A 1°x1° grid counting the number of a) anti-cyclonic eddies and b) cyclonic eddies to form in each grid cell between October 1992 and April 2012.

Results show a concentration of eddy dissipation near to the southern African coast with up to 14 anti-cyclonic (Figure 12a) and 12 cyclonic eddies (Figure 12b) dissipating in the northern Agulhas region between October 1992 and April 2012.

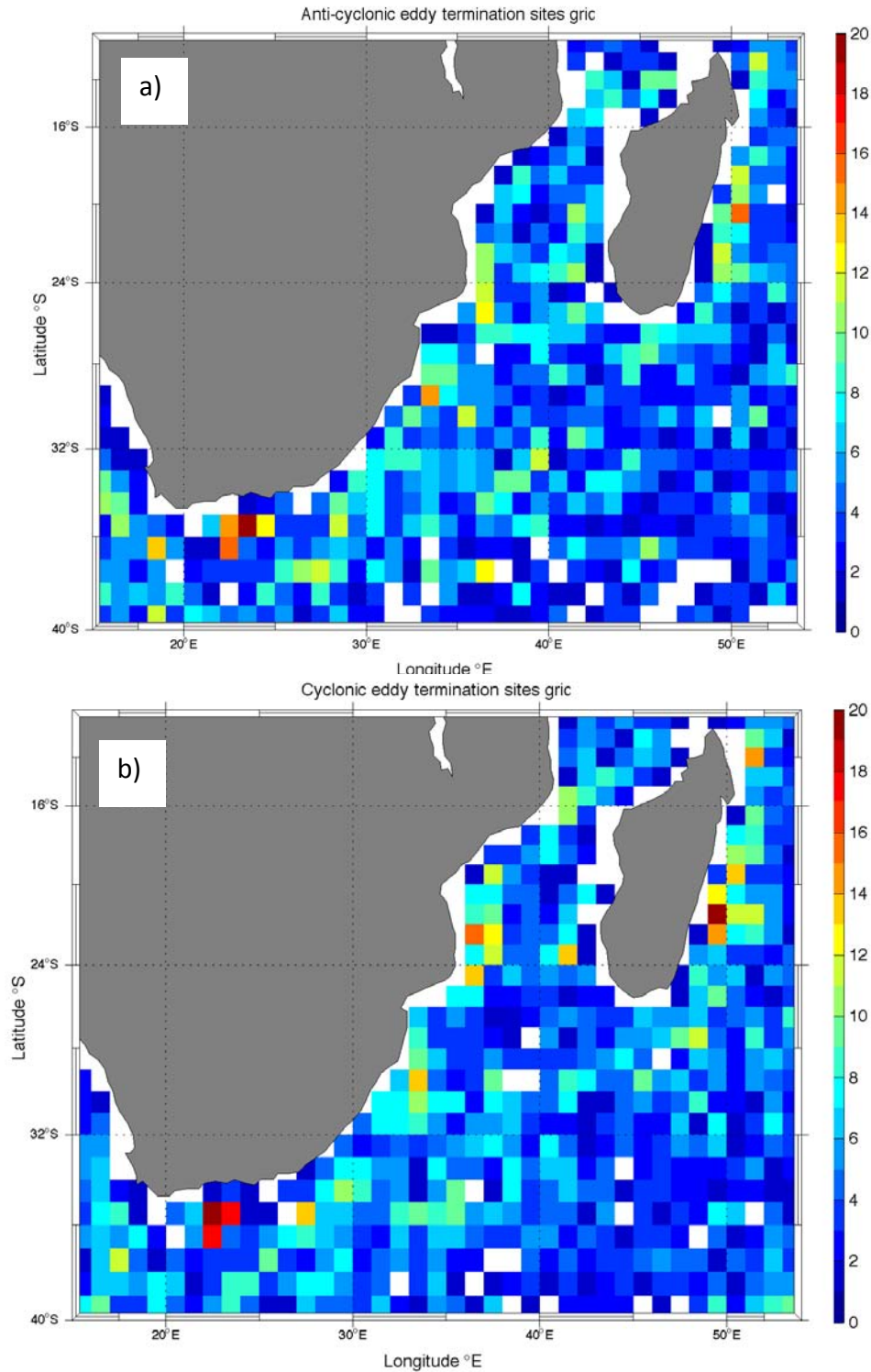


Figure 12: A 1°x1° grid counting the number of a) anti-cyclonic eddies and b) cyclonic eddies to terminate in each grid cell between October 1992 and April 2012.

A subset of the data set, which selected only those eddies which interact with the southern Madagascan coast between October 1992 and April 2012 (Figure 13), shows a bias towards cyclonic eddy formation. Of the 356 eddies selected by the subset, 40.2% were anti-cyclonic and 59.8% were cyclonic. On average, 18 to 19 eddies form per year, of which 7-8 are anti-cyclonic and 10-11 are cyclonic (Table 2). A majority of 74.7% of the eddies which move near the southern Madagascan coast form in the region South of Madagascar. The remaining 25.3% form to the east of the island. Between 4 and 5 eddies form east of Madagascar every year. Approximately 2-3 are anti-cyclonic and 2-3 are cyclonic.

Subsetted eddies	No. anti-cyclones/year	No. cyclones/year
Formed south of Madagascar	5-6	8-9
Formed east of Madagascar	2-3	2-3
Total	7-8	10-11

Table 2: A table showing the average frequency of eddy occurrences south of Madagascar per year for the subsetted data.

These results indicate that between October 1992 and April 2012, very few of the anti-cyclonic eddies which interacted with the Madagascan coast, successfully crossed the Mozambique Channel to interact with the African coast (Figure 13a). Many more cyclonic eddies were able to cross the southern Mozambique Channel, most of which dissipate shortly afterwards (Figure 13b). As the satellite altimetry data cannot be used to track eddies when they get too close to the coast, it may be that eddies move closer to the coast than suggested by the eddy tracking data. Because of this limitation, it is not possible to quantify, with the eddy tracking data set alone, exactly how many eddies reach and interact with the African coast. A frequency plot of the subset data however, shows approximately 1 eddy per year, usually cyclonic, which has previously interacted with the southern Madagascan coast, moves close to the southern African coast (Figure 14). Mean Sea Level Anomaly (MSLA) data from AVISO, were used to confirm that there are eddies which

interact with both the Madagascan coast, as well as the African coast (Figures not shown).

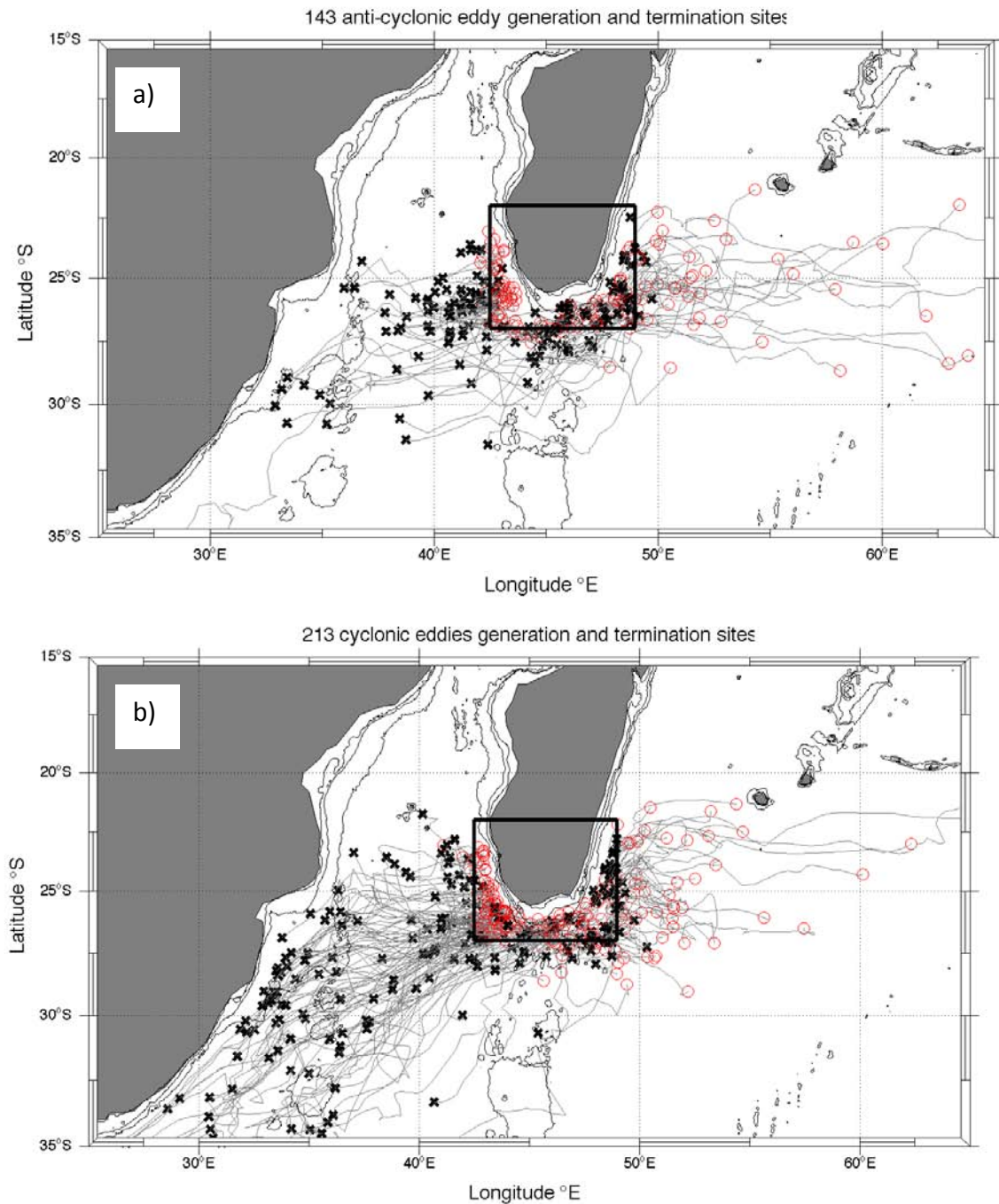


Figure 13: The origin and dissipation of (a) anti-cyclonic and (b) cyclonic eddies that moved close to the southern Madagascan shelf (black rectangle) between 1992 and 2012. Red circles indicate regions of formation whereas black crosses indicate an eddies' termination point according to the eddy tracking data set. The grey lines show the trajectories of the eddies and the black lines show the bathymetry.

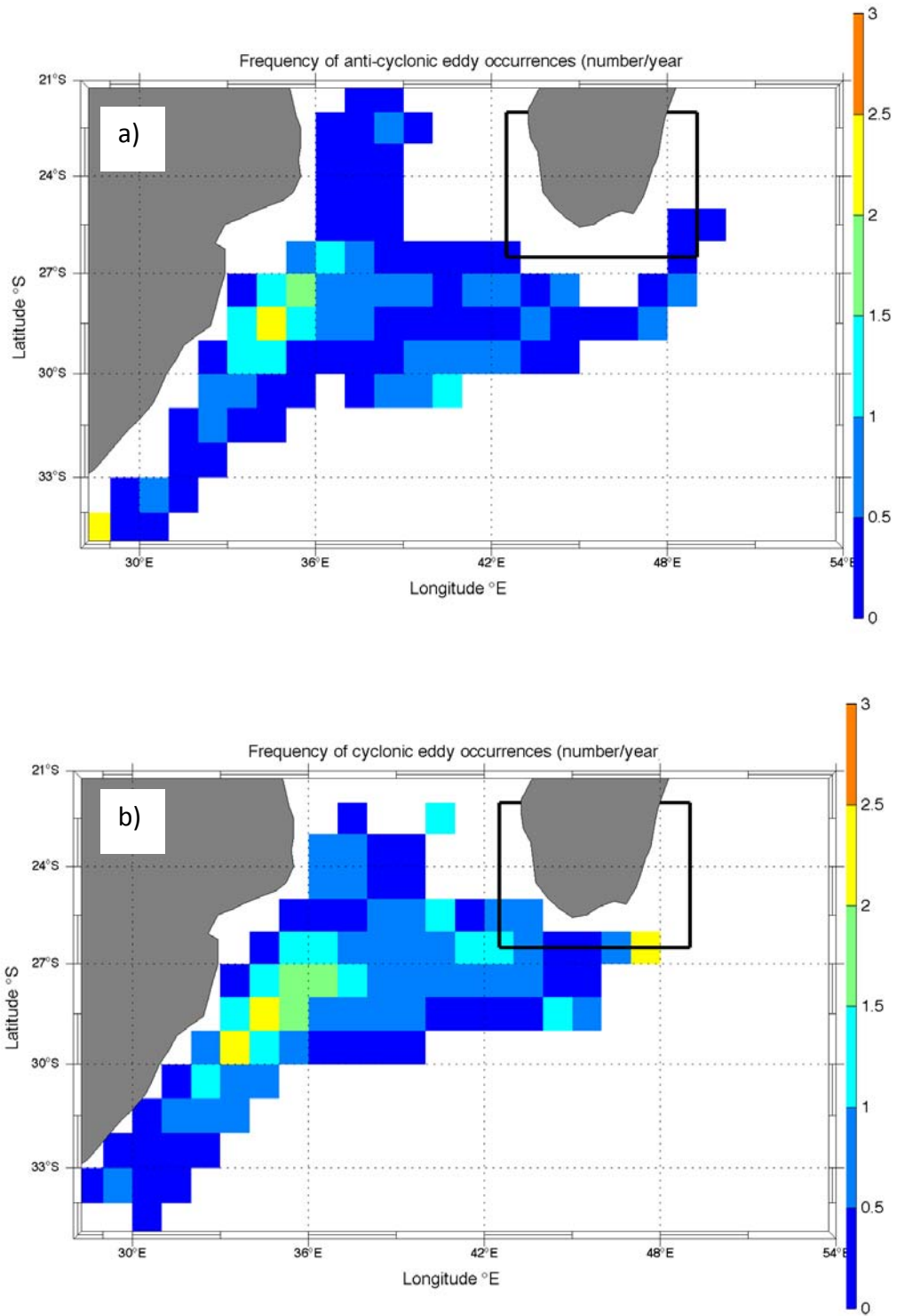


Figure 14: A 1°x1° grid counting the frequency of (a) anti-cyclonic and (b) cyclonic eddy occurrences per year in the subsetting eddy tracking data. Only those eddies which interact with the southern Madagascan coast (the region denoted by the black rectangle) were selected.

An investigation into the properties of the subsetted Madagascar eddies shows that as eddies propagated away from Madagascar and across the southern Mozambique Channel, their amplitudes increase from 0-5cm to a maximum of 30-50cm before decreasing again as they dissipate (Figure 16a). Amplitudes of Madagascar eddies decrease near to the Agulhas Current or African Coast. A 1°x1° grid of all of the eddy tracking data shows the amplitude of Madagascar eddies to be almost the same as those eddies propagating down the Mozambique Channel (Appendix, Figure 1). The radii of the Madagascar eddies also increase from 40-70km to a maximum of more than 100-150km as eddies move away from Madagascar and towards the African coast (Figure 16b). Considering all eddy data suggests that eddies propagating down the Mozambique Channel have, on average, 20-30km larger radii than Madagascar eddies (Appendix, Figure 2). The data suggest that Madagascar eddies that successfully propagate across the southern Mozambique Channel, decrease their radii upon interacting with the Agulhas Current or African coast until the eddies dissipate completely. The same is true for the circum-averaged speed (rotational velocity) of the Madagascar eddies. Circum-averaged speed increases from 0-10cm/s to 50-100cm/s as eddies cross the channel (Figure 16c). This is a similar but slightly lower circum-averaged speed (approximately 10cm/s) to the Mozambique Channel eddies (Appendix, Figure 3). Although some eddies dissipate before reaching the Agulhas Current, those which do interact with the current or African coast line begin to dissipate and their circum-averaged speeds decrease until the eddy is no longer tracked by the eddy tracking algorithm because of the eddies' proximities to the coast.

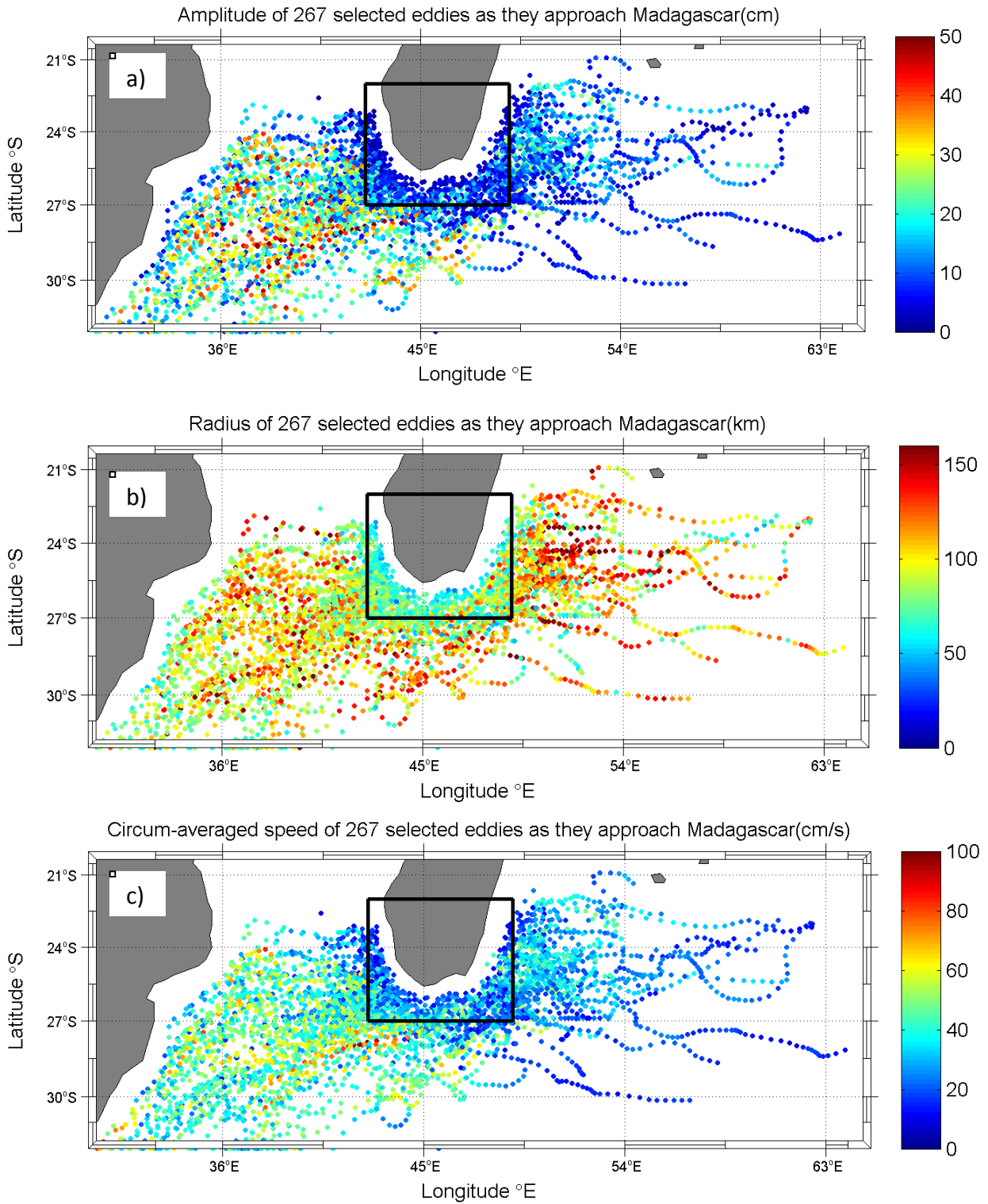


Figure 16: An image showing (a) the amplitudes, (b) the radii and (c) the circum-averaged speeds of 267 eddies which travelled near to the southern Madagascan coast

Results from a calculation to see whether or not water is conserved in Madagascar eddies as they cross the southern Mozambique Channel indicate that in over 98

percent of eddies water is conserved (Figure 17). If water is conserved in eddies for the duration of their channel crossing, this confirms their ability to transport unique water masses and potentially organisms across from Madagascar to the southern African coast.

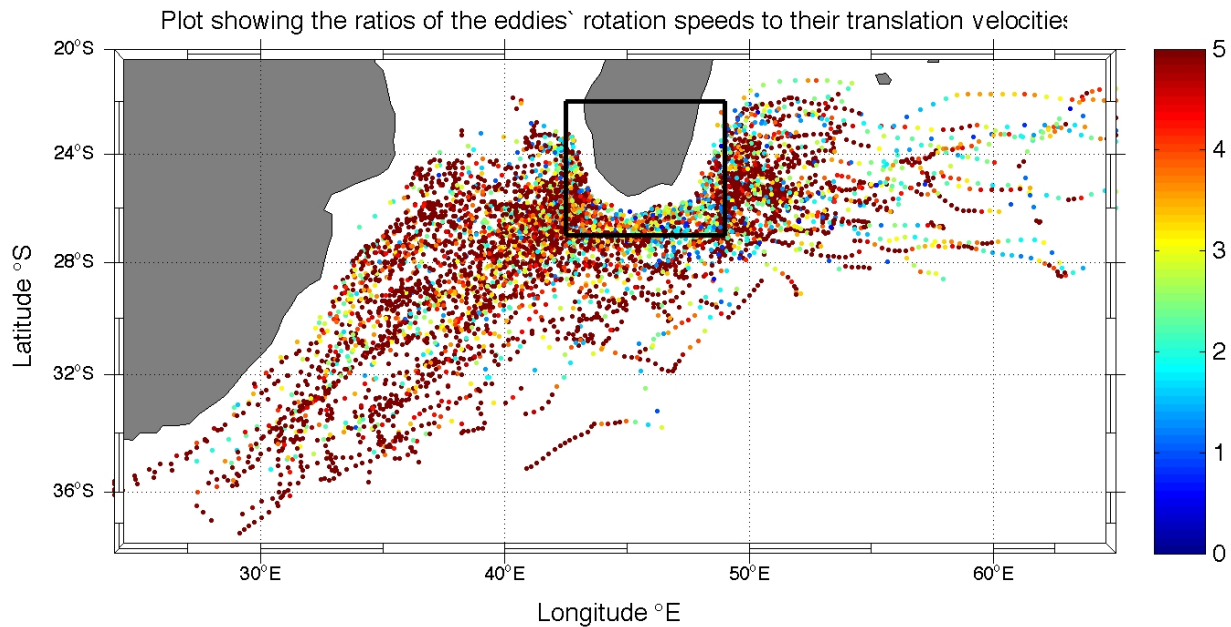


Figure 17: The maximum eddy rotation speed is greater than the translation velocity for almost every eddy tracked. For all values greater than 1, water is conserved in the eddy.

These results confirm that a pathway between southern Madagascar and southern Africa exists, and suggests that approximately once a year, it is possible for biota to be swept into an eddy and transported across the southern Mozambique Channel to the African coast.

4.5 Ocean colour data

The interaction of eddies with the coast is not clear using the Chelton data and therefore chlorophyll-a data were used. The southern Madagascan coastal waters are rich in chlorophyll-a and results from mean monthly chlorophyll-a observations show eddies drawing off these coastal waters into their periphery as they pass Madagascar. This confirms that eddies do in fact interact with and contain

Madagascan coastal waters and therefore are a potentially viable transport mechanism for organisms (Figure 18).

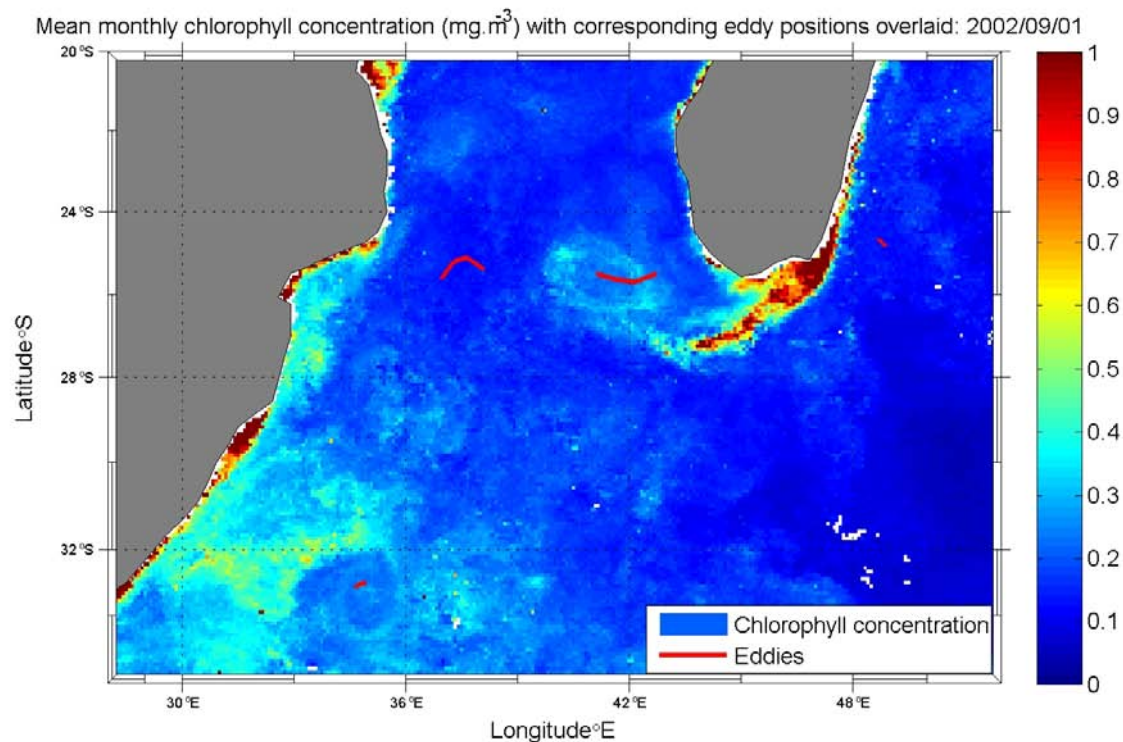


Figure 18: The mean monthly chlorophyll-a concentration in mg.m^{-3} with the corresponding center eddy positions for the same month overlaid.

It was thought that some circulation features would be missed with monthly averages of the chlorophyll-a data, and therefore daily data were also used. From daily chlorophyll-a observations, a small retroflection of the South East Madagascar Current as well as the formation of a cyclonic eddy on the lee side of the current is evident (Figure 19). This retroflection is believed to be responsible for the formation of anti-cyclonic eddies south of Madagascar.

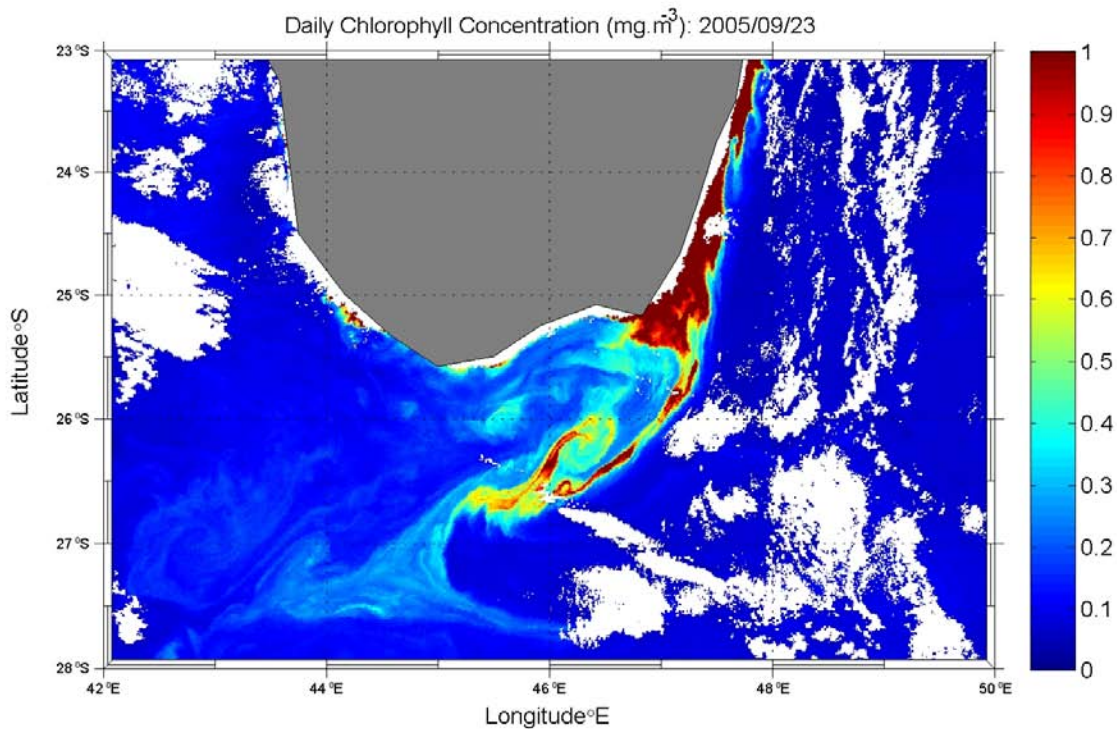


Figure 19: The daily chlorophyll-a concentration in mg.m^{-3} off southern Madagascar.

4.6 Water mass retention

The Chelton data, overlaid on weekly MSLA data, were used to track several case study eddies from the subset, to see if the eddies which interact with the southern Madagascan coast were also interacting with the southern African coast. However, as the Chelton data set ends in April 2012, it was not suitable for tracking the eddies which have occurred in 2013. Several research cruises were conducted in 2013 where in-situ data were collected to better understand the properties and dynamics of these eddies.

Two drifters were deployed on 12.04.2013 in a cyclonic eddy. The trajectories of these drifters indicate that the drifters remained in the eddy until it began to interact with the South African coast, at which point the drifters were swept down the Agulhas Current and onto the South African coast (Figure 20).

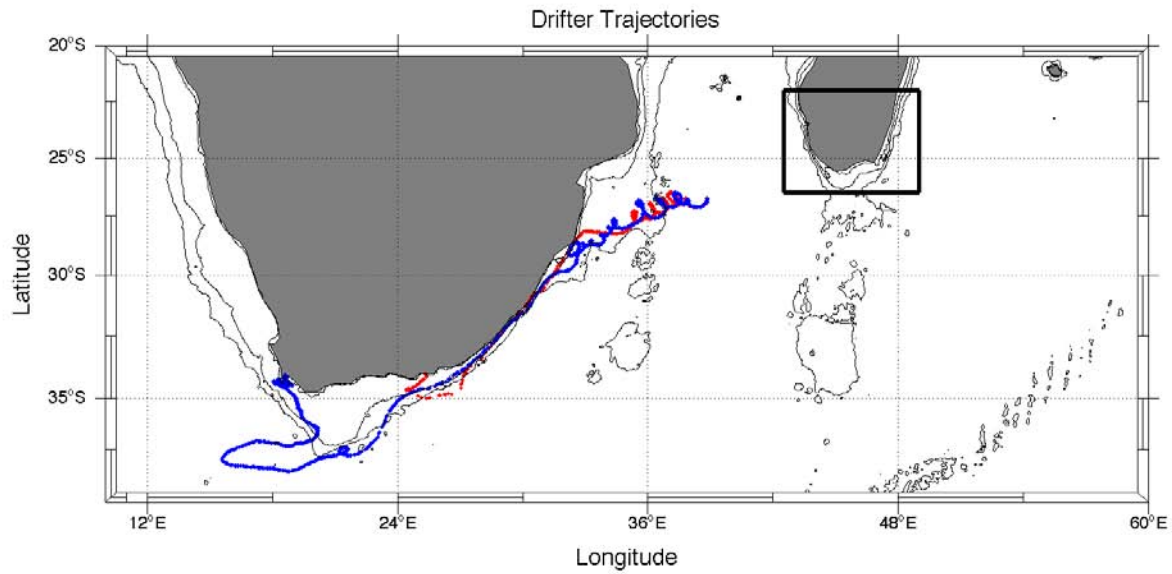


Figure 20: The trajectories of 2 SVP surface drifters deployed in a cyclonic eddy on 12.04.2013 at $26^{\circ}44.4556'S$ and $38^{\circ}20.089'E$. The eddy originated from southern Madagascar. Bathymetry is shown by black contours.

Results indicate that it could be possible for drifters to be transported across the southern Mozambique Channel in an eddy. A further comparison of the drifters' trajectories overlaid on the MSLA, confirm that the drifters remain in the eddy as they approach the coast (Figure 21). Drifter 14925 is the first to emerge from the eddy, with drifter 14928 being swept out the eddy shortly afterwards, as the eddy interacts with the coast.

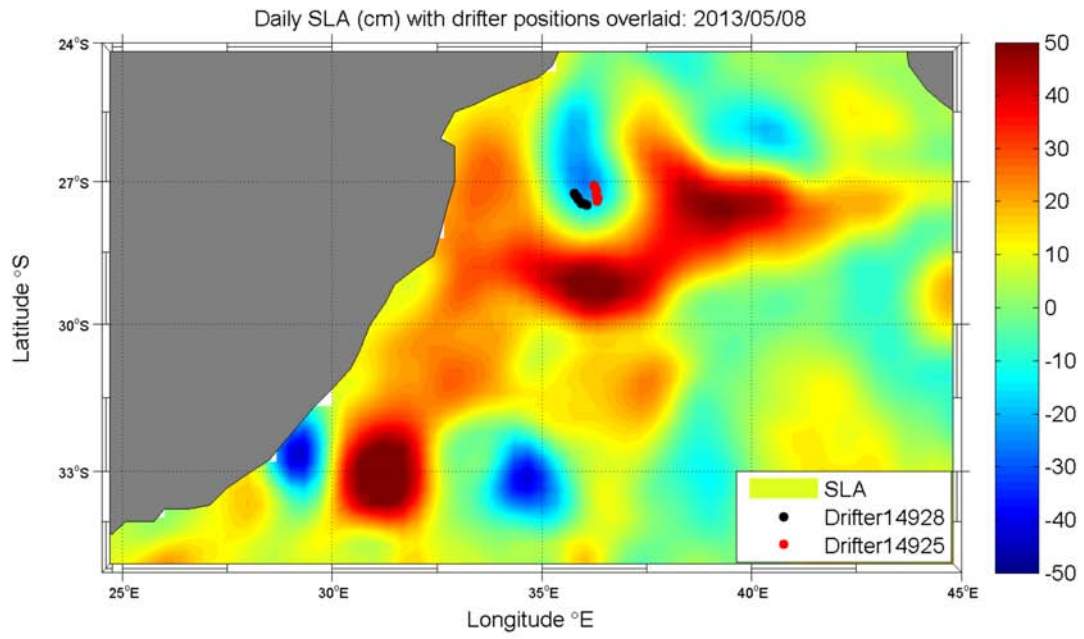


Figure 21: The AVISO MSLA with the two corresponding surface drifter positions overlaid.

5. Discussion

The overall aim of this study was to determine whether a potential eddy pathway for the transport of biota from southern Madagascar across the southern Mozambique Channel to southern Africa exists (Figure 22). This pathway comprises of three components:

1. The entrainment of biota from the Madagascan shelf into eddies
2. The retention and transport of biota across the channel to the African continent.
3. The deposition of the biota onto the African shelf.

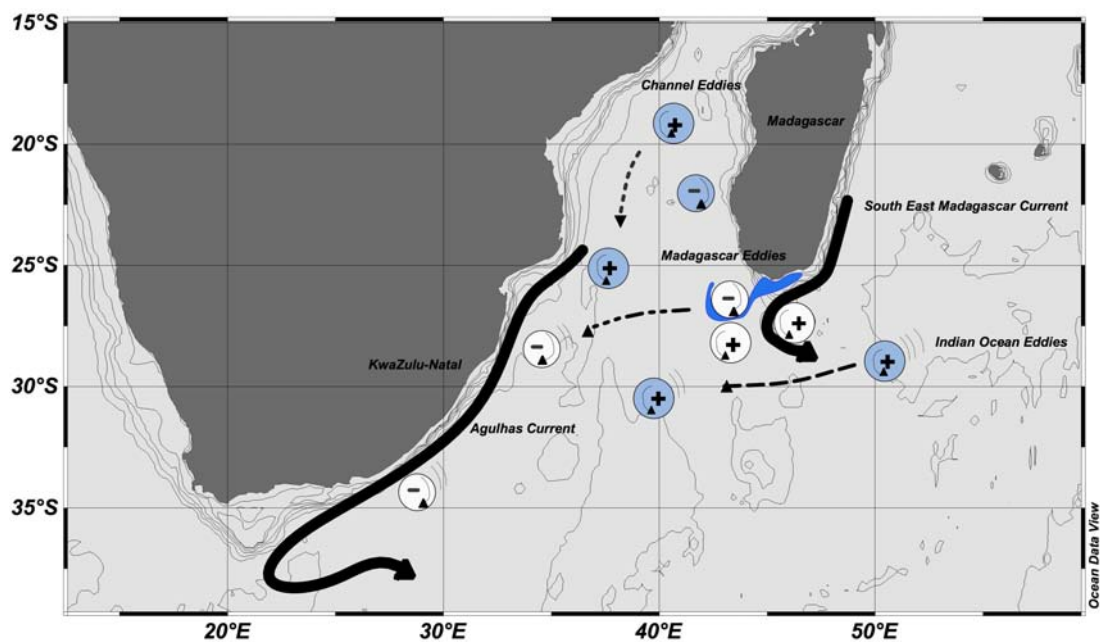


Figure 22: The source region eddies of the Agulhas Current. Cyclonic and anti-cyclonic eddies from the Mozambique Channel, southern Madagascar and from the Indian Ocean are shown to propagate in the direction of the Agulhas Current. Interaction of eddies with the Agulhas Current and propagation along the offshore edge of the current is indicated. Anti-cyclonic eddy formation as a result of the South East Madagascar Current (SEMC) retroflexion is suggested. Eddy dipole formation south of Madagascar is shown, as is the interaction of eddies with the Madagascan coastal waters (shown in blue).

Using the Chelton eddy tracking dataset from 1992-2012, it has been shown that eddies form near, or pass close to the southern Madagascar coast. Moreover, more cyclonic eddies interact with the Madagascan coast than anti-cyclonic eddies due to the fact that cyclonic eddies form on the inshore edge of the SEMC, which is near to the coast (Figure 13). It is possible that some anti-cyclonic eddies have been excluded from the subset because they formed south of the subset domain and therefore were not included due to their lack of interaction with the Madagascan coastal waters. It has been shown using TSG data that the water in anti-cyclonic eddies consists primarily of water from the East Madagascar Current and could therefore also contain less saline coastal waters (Figure 6). Results from the statistical analysis in this study indicate that 18 to 19 eddies interact with southern Madagascar annually, of which 59.8 % are cyclonic (Figure 13). Only 4 to 5 of these eddies are formed east of the sub-continent each year. A study by Ridderinkhof et al. (2013) shows approximately 4 to 6 dipoles occur annually. Therefore, these results suggest that not all eddies forming south of Madagascar are dipoles. Results from Figure 16b show the radii of Madagascar eddies to increase from 40-70km to 100-150km as the eddies move into more open water and cross the channel and are comparable with previous studies (de Ruijter et al., 2004; Ridderinkhof et al., 2013; Halo et al., 2013).

AVISO Mean sea level anomaly data and satellite-derived chlorophyll-a data were used to confirm that the eddies in the Chelton data set were in fact interacting with the coast. Coastal waters on the southern shelf of Madagascar are high in productivity as a result of the upwelling which occurs on the eastern side (Quartly and Srokosz, 2004). Using chlorophyll-a data as a tracer, it was clearly visible that passing eddies pull off coastal waters into their peripheries (Figures 18 and 19). This process is not new. Ocean colour has previously been used to show that eddies carry chlrophyll-ladden coastal waters offshore (Quartly and Srokosz, 2004; Tew-Kai and Marsac, 2009) but for the purposes of this study, these results indicate coastal organisms could therefore also potentially be drawn away from the coast and into an eddy. This suggests that the first stage of the eddy vector hypothesis is plausible.

The eddy tracking data indicated that eddies propagate from Madagascar to southern Africa and retain their water mass characteristics. Therefore, there is a potential to transport larvae across the southern Mozambique Channel. The results also show that eddies forming south of Madagascar are smaller and less energetic than those forming in the Mozambique Channel. The radii of Mozambique Channel eddies are on average 20-30km larger and the circum-averaged speed is approximately 10cm/s greater. Although the Madagascar eddies are not as big as those formed in the Mozambique Channel, this study shows through calculation and through drifter tracking, Madagascar eddies are able to conserve their water as they cross the southern Mozambique Channel (Figures 17, 20 and 21). Clearly drifters are much larger than planktonic larvae or other rafting biota, but the retention of the drifters in the cyclonic eddy for an extended period of time together with the drifters' interactions with the southern African coast, could be an indication of possible larval transport.

Upon reaching the African coast, eddies appear to dissipate (Figure 12). Results in Figure 12 show more eddies dissipate near the southern African coast than in the open ocean. This is possibly due to the interaction of the eddies with the Agulhas Current and the continental shelf, which could cause the eddies to become weaker and dissipate. As the Chelton data set is derived from satellite altimetry, there is no data near to the coast and the precise point of dissipation cannot be determined from this data set alone. However, this result is consistent with the results shown in the study by Chelton and Schlax (2011) showing that the trajectory of an eddy often ends near the east coast of a continent. As many eddies dissipate near to land, any biota entrained in the eddy would be released and this would explain why organisms on the southern African coast could have genetic similarities to those of Madagascar. The drifters used in this study were used to confirm the weakening of an eddy upon its interaction with the African shelf and the potential release of biota from the eddy (Figures 20 and 21).

The case studies undertaken in this thesis were used to confirm that eddies are in fact crossing the Mozambique Channel (Figures 7, 8, 9 and 10). In one case study

(Figure 10a), the interaction of the cyclonic eddy with the African coast causes the eddy to become elongated and the mesoscale feature begins to progress down the Agulhas Current. A similar situation was observed in Morris et al. (2013). The elongated shape is possibly representative of a filament of water trailing behind the eddy as described in previous research by Shi and Nof (1993) and Nof (1999). It is thought that the filament could be a mechanism whereby organisms could be released from the eddy at the African coast and not swept down the Agulhas Current. In order for the “Suitcase hypothesis” to be valid, an organisms needs to become entrained in an eddy, travel across the southern Mozambique Channel be deposited at the African coast. Results from the case study therefore support the hypothesis.

Usually only cyclonic eddies are able to successfully cross the southern Mozambique Channel to interact with the southern African coast at a frequency of 1 per year (Figure 14). The presence of an eddy at the northern KwaZulu Natal coast has been shown to cause a drop in temperature as described by Roberts (2006) and Morris et al. (2013). This implies that once a year, the opportunity exists for organisms to travel from southern Madagascar to the southern African coast in an eddy.

In summary, this study has shown that eddies formed south of Madagascar are able to cross the southern Mozambique Channel and interact with the African coast at least on one occasion each year. Eddies therefore, can potentially provide a vehicle for the transport of biota such as the larvae of the spiny lobster *Panulirus homarus rebellus* across the southern Mozambique Channel- supporting the “Suitcase” hypothesis. However, only the results of the genetic studies which compare the similarities between the Madagascar and Africa populations, and hence the connectivitiy will ultimately test the hypothesis.

6. Conclusion

The dynamics and interactions of mesoscale eddies with the Southern Madagascan coast have been investigated in this study. Results show that although dipoles often form, there is a bias towards cyclonic eddy formation and interaction with the southern Madagascan coast. From chlorophyll-a observations it is evident that the eddies are drawing off nutrient rich coastal waters into their peripheries. This is a viable method for the entrainment of biota into eddies. After interacting with the southern Madagascan coast, this study shows that the circum-averaged speed of Madagascar eddies is greater than their translation speeds. This along with drifter retention in the eddies confirms that water is conserved in the eddies as they cross the southern Mozambique Channel and it is thought that the drifters, although larger, could be indicative of planktonic larvae retention in eddies. Case studies show that eddies take several months to cross the southern Mozambique Channel and therefore, organisms with a longer larval phase would be more likely to survive the Channel crossing. It is interesting to note that more of the cyclonic eddies successfully cross the southern Mozambique Channel at a frequency of approximately 1 per year to interact with the southern African coastal waters. Many eddies dissipate or become elongated upon reaching the African coast and it is thought that organisms could be released from eddies here. Eddies are therefore a potentially viable vector for the transport of planktonic larvae and water masses across the southern Mozambique Channel and could explain the genetic similarities between organisms occurring on the southern African coast and those found in southern Madagascar. Further genetic studies need to be undertaken to determine the extent of the connectivity between Madagascar and southern Africa. A more detailed study of the interstitial or frontal flow between eddies should also be undertaken as it is possible that a faster and more frequent pathway between Madagascar and the southern Madagascan coast could exist.

Acknowledgments

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The eddy tracking dataset used in this study was developed by Dudley Chelton and Michael Schlax is available from <http://cioss.coas.oregonstate.edu/eddies/>. The Mean Absolute Dynamic Topography and Mean Sea Level Anomaly data used in this study were obtained from <http://www.aviso.oceanobs.com/duacs/> and were produced by Ssalto/Duacs and distributed by AVISO with support from Cnes. Sea surface temperature data from Operational Sea Surface Temperature and Sea Ice Analysis (OSTIA), available at <http://ghrsst-pp.metoffice.com>, were used in this study. Chlorophyll-a data from the MyOcean website (<ftp://myocean.artov.isac.cnr.it/core/>) and <ftp://www.afro-sea.org.za/> were used. SVP Drifters from the Global Drifter Programme were deployed and the data were retrieved at <http://www.aoml.noaa.gov/phod/trinanes/xbt.html>. Thanks go to Tammy Morris and Santjie du Toit for their help in sourcing and deploying drifters for my project. I am thankful to Dr Martin Visbeck and the crew and scientists on board the R/V Meteor M100_2 cruise for the Thermosalinograph and in-situ data they collected for this study. Underwater Temperature Recorder data from the Centre for in situ Observation Oceanography were used (<http://www.cfoo.co.za>). The ETOPO2 topography data were taken from the National Oceanographic and Atmospheric Administration (NOAA) website (<http://www.ngdc.noaa.gov>).

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Appendix

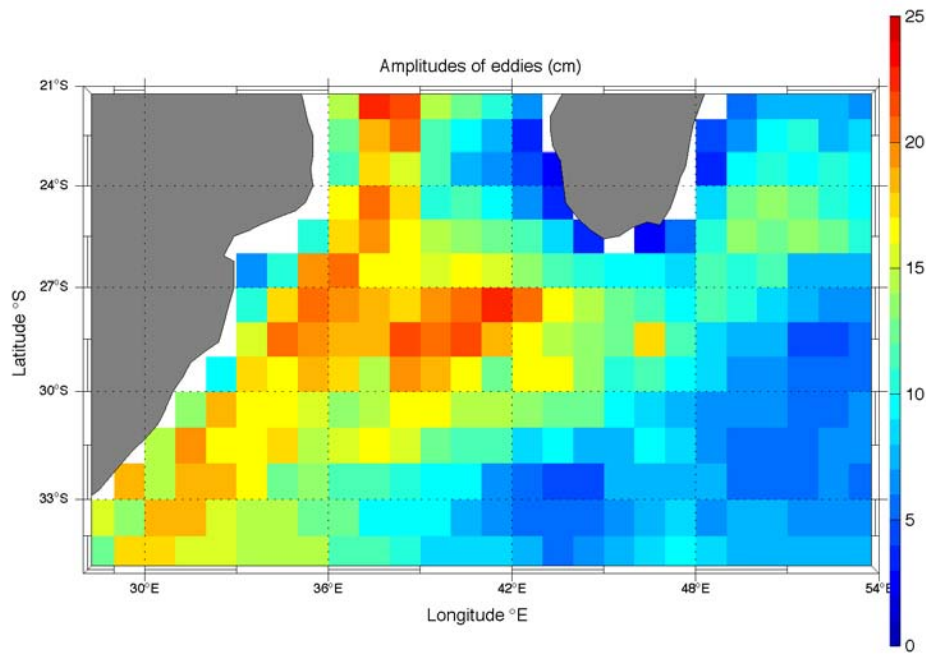


Figure 1: A 1°x1° grid showing the average annual amplitude (cm) of both anti-cyclonic and cyclonic eddies from October 1992 until April 2012.

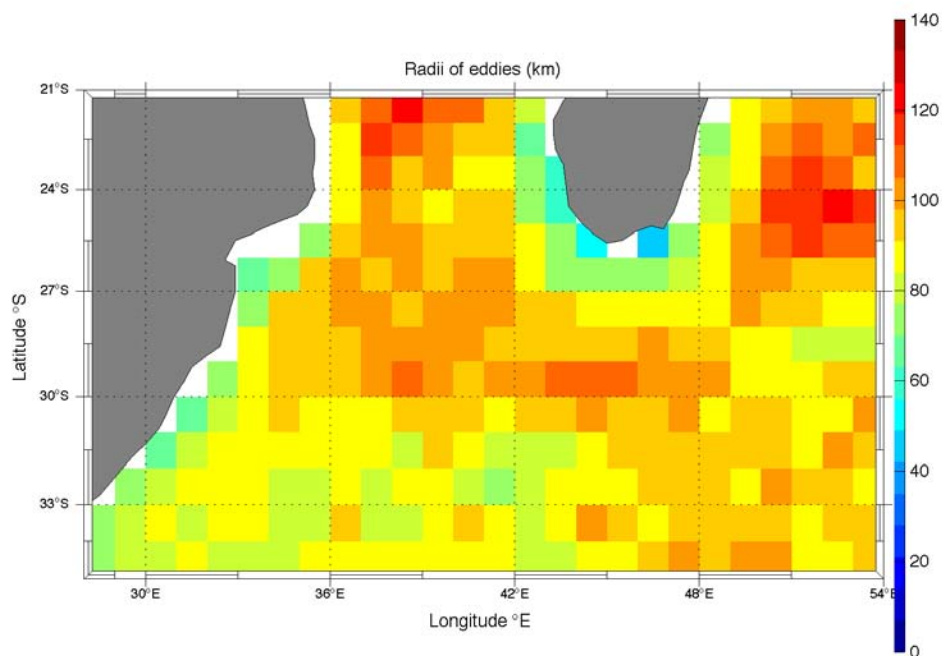


Figure 2: A 1°x1° grid showing the average annual radius (km) of both anti-cyclonic and cyclonic eddies from October 1992 until April 2012.

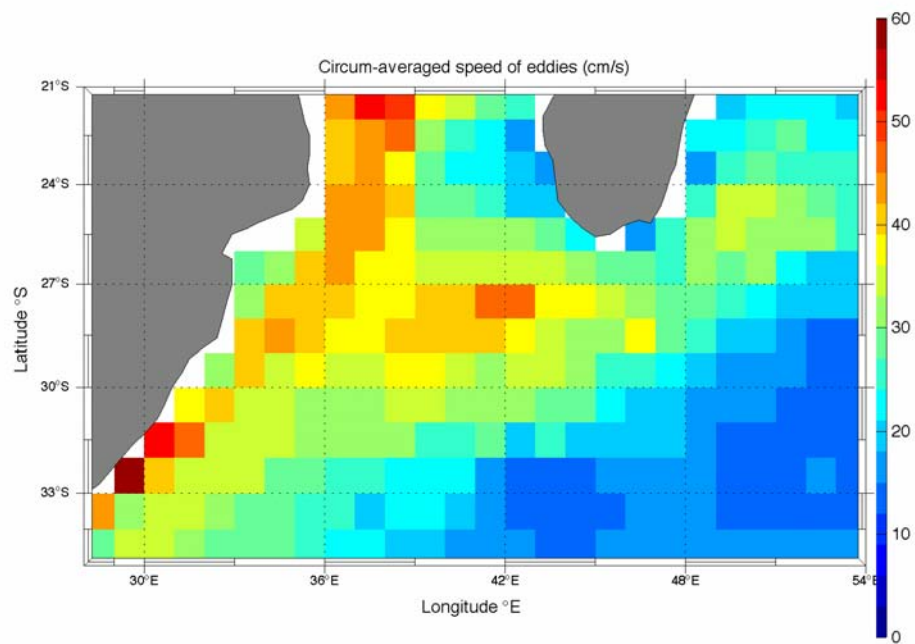


Figure 3: A 1°x1° grid showing the average annual circum-averaged speed (cm/s) of both anti-cyclonic and cyclonic eddies from October 1992 until April 2012.